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STUDIES OF THE EFFECTS OF GRAVITATIONAL AND INERTIAL FORCES ON CARDIOVASCULAR
AND RESPIRATORY DYNAMICS

The major portion of this report consists of the following manuscripts:

I. The Television Camera in Dynamic Video Angiography -

This is a description of the characteristics of television cameras which affect their capability to resolve dynamic changes in position and shape of rapidly moving objects, such as the left ventricle. This study demonstrates that the temporal resolving capabilities of conventional television camera systems using the interlaced scanning mode of operation are inadequate for the type of dynamic ventriculographic studies which would be suitable for study of cardiac function in large primates during space flight. Cameras with adequate temporal resolution in such studies can be obtained by using noninterlaced operation of camera tubes whose photosensing targets have image retention (sticking) characteristics of less than five percent after a single scan.

II. Dynamic Computer Generated Displays for Study of the Human Left Ventricle -

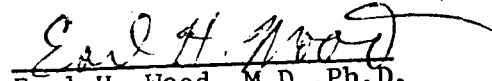
This is a description of the multidimensional computer graphic and display techniques which have been developed in this laboratory to facilitate the comprehension and analysis of the very large volumes of data obtained by the biplane roentgen videometry systems which are required to study the temporal and anatomic relationships of the changes in shape, pressure, and associated myocardial length-tension relationships from instant-to-instant during individual heart beats. It is believed that these techniques will lead to improved methods for study of cardiac function which are applicable to study of possible alterations which may be induced by changes in the gravitational-inertial force environment, such as may be encountered in space flight.

III. A status report on the Work Statement for the sixth year (November 1, 1972-

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October 31, 1973) of this research grant (dated August 31, 1972).

IV. A list of publications covering the period October 1, 1971 to October 1, 1972.


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September 29, 1972

EHW:JF

I. THE TELEVISION CAMERA IN DYNAMIC VIDEO ANGIOGRAPHY

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ABSTRACT

Ritman EL, Johnson SA, Sturm RE, Wood EH: The television camera in dynamic video angiography

Three characteristics of conventional television cameras--image integration and storage, interlaced scanning, and image retention--make these cameras unsuitable for dynamic angiography. Use of noninterlaced scanning and synchronized 60/sec pulsed operation of the x-ray source avoids degradation of temporal resolution caused by image integration and provides discrete video images at 60/sec if cameras with minimal image retention are used. Image orthicon, lead monoxide vidicon, and silicon diode integrated target epicon camera tubes have less than 10% image retention after single scans and are suitable for angiography. Stop-action photographs of television displays confirm the poor temporal resolution of conventional cameras.

Key words: Angiography

Cardiac dynamics

Left ventricle

Photoelectric

Pulsed x-ray

Stroke volume

Temporal resolution

Ventricular volumes

Video camera tubes

Videodensitometry

Videometry

Video roentgenography

Video scanning

Introduction

The use of video techniques in the recording and measurement of roentgenographic images is becoming increasingly common. In general the video chain consists of a television camera which is focused onto the optical output phosphor of an image intensifier system which converts, with amplification, x-ray photons to optical photons. The video signal may be either viewed directly, before or after on-line processing, or recorded for subsequent viewing and analysis of specially processed or unprocessed images. Because of the great speed and relative facility of video image manipulation, video techniques greatly facilitate application of special electronic and digital techniques for intensification or enhancement of particular aspects of images plus the automated analysis of image information. It appears probable that these potentially valuable techniques will continue to be developed and accepted.

Although broadcast-compatible video cameras produce satisfactory images for most entertainment purposes, these images are not suitable for quantitative measurements of variations in either the dimensions or the luminosity of objects of interest in these images. Commercial television systems therefore must be altered in order to produce images (video signals) which will allow full use of the capabilities of combining electronic data processing and computing techniques for quantitative measurement applications.

The purpose of this paper is to describe some characteristics of video camera tubes which may affect the information content of video angiograms. Because the effect of the transfer characteristics of the camera can be especially significant in dynamic angiography, several types of distortion and methods for their elimination or reduction will be described.

The Video Image

In the United States broadcast quality images are generated by television equipment in accordance with standards governing the timing relationships of a variety of electronic wave forms, which ensure that pictures created at the source (the studio or a remote location) may be viewed in synchronism on millions of receivers throughout the country.

A scanning rate of the photo target of the television camera at power line frequencies (i.e., 60 scans [fields] per second) minimizes problems of synchronization. Each successive field (image) is "read" off the target by an electron beam in a vertical succession of horizontal scan lines (raster) which covers its full vertical dimension. Similarly, these images are displayed by an analogous electron beam which "writes" these images simultaneously in an identical set of horizontal lines on the face of one or more standard television sets (video monitors).

In order to achieve the maximum vertical resolution of video images (i.e., the number of horizontal lines) and

to obtain the optimum combination of horizontal sweep speed and frequency band-width of the electronic circuitry required to provide adequate resolution in the horizontal dimension, the horizontal lines of successive fields are interlaced to form video frames, as illustrated in Figure 1. This arrangement provides a slower horizontal sweep speed (increased horizontal resolution) while still retaining a "refresh rate" of 60/sec on the display screen. A refresh frequency of 60 Hz exceeds the flicker-fusion frequency of the human eye so that a flicker-free display results.

A video field consists of approximately $262\frac{1}{2}$ lines which are nearly horizontal and which are interlaced with a second field of as many lines to create a frame containing 525 horizontal lines. Successive fields may be designated as odd or even, depending on whether the odd or even lines (as counted from the top of a complete frame) are scanned during each cycle. Only about 500 of these horizontal lines can be used to form an image, since the last $12\frac{1}{2}$ lines of each field occur in a period known as the vertical blanking interval; this period serves to synchronize images and during this time the electron beam is repositioned at the top margin of the image to start the next scan.

The scanning electron beam, controlled by synchronizing pulses, sweeps across the back surface of the photo target of the camera or display screen and may start at the left end of line 1, sweeping its length to the right

edge of the image in $52.5 \mu\text{sec}$. At the end of this period, the beam is blanked out, returned to the opposite edge, and relocated within $11 \mu\text{sec}$ to a position enabling it to scan line 3 and so on. When the scan of odd lines at the bottom of the raster is complete the vertical blanking interval (about 1 msec) occurs, during which time the beam is returned to a point midway between previously scanned lines 1 and 3 so as to enable it to scan the even lines, starting with line 2. This pattern is repeated indefinitely, creating odd and even fields and interlacing them, so as to create flickerless images (Fig. 1).

The electronic information (voltage) generated by the sweeping electron beam combined with the standard synchronizing pulses varies during each horizontal scan according to picture content at the particular cross section of the image being traversed by the specific scan line. Bright areas in the picture will result in larger values of the signal voltage, while dark areas will be represented by lower amplitudes in the voltage versus time plot produced by the scan of single horizontal line as viewed on an oscilloscope (Fig. 2). The negative square-wave voltage pulse A is the synchronization pulse for alignment of successive horizontal video lines during which the scanning beam is reset to the left side of the image (both in the camera and the video display tube). The zero-voltage interval B

(called the sync pulse back porch) is the reference level (ground potential), to which the video signal may be clamped at the onset of each horizontal line. Special circuitry to "hard clamp" the onset of each video line to a fixed voltage reference must be incorporated in conventional television systems to adapt them for use as quantitative instruments for measuring variations in the intensity and spatial distribution of incident light on the photo target of the camera tube (1,2). The voltage level C is set to a standard level (usually 0.05 volt) when the incident light on the input phosphor is zero (i.e., "black level").

As the video scanning beam sweeps across the image, its voltage is proportional to the brightness of the image. In this case, a dark object (e.g., an opacified left ventricle) is present in the central portion of the image so that the voltage of the video signal is high as it traverses the bright portion of the image (e.g., the lungs). (Fig. 2 D), decreases as it crosses the ventricular silhouette (E), and then increases again over the bright portion of the image (F). If a monochromatic roentgen beam could be used and the effects of scattered radiation in the thorax and light scattering in the intensifier tube are minimal, the difference between the logarithm of the voltages above dark level--(D-C) and (E-C)--is proportional to the difference in roentgen opacity of the lung field and opacified left ventricle traversed by this particular horizontal line.

Types of Video Cameras

There are several types of video cameras. They differ mainly in the nature of the light sensing photo target and in the method of converting images focused on this photo target into their electrical analogs. Camera tubes, when grouped according to principle of operation, fall into two main classes: return beam tubes (such as the image orthicon) and nonreturn beam tubes (such as the common vidicon).

Vidicon.--The vidicon, currently the most universally used video camera tube, is more reliable for most general purpose applications and less expensive than the image orthicon, and is less complicated to use. A focused electron beam from a source at one end of an evacuated glass tube is accelerated toward the other end of the glass tube and deflected in the regular video raster manner (Fig. 1) by either electric or magnetic fields. The camera tube photo target (size, in one type, about 0.375 by 0.5 inch) is laid down on the inner surface of the tube face plate. The target contains a photoconductive material such as antimony trisulphide (original vidicon) or lead monoxide (e.g., plumbicon); more recently epicon cameras with targets consisting of arrays of silicon diodes have been made. In simplified terms, the electrical conductivity of the target varies with the amount of, and in spatial conformity with, the light falling on its surface so that the amount of the impinging electron

beam which is conducted by the target is proportional to the amount of light that has fallen on the particular site. The variations in target current, as the target is scanned, therefore vary temporally and in correct spatial relationship with changes in illumination at each site on the target scanned by the electron beam. In the newer vidicons the target materials have increased sensitivity and dynamic range and low post-scan image retention and thus are more suitable for roentgen angiography.

Image Orthicon.--The image orthicon camera, more complex and expensive than the vidicon, is less widely used. Nonetheless, it is very sensitive and some types have negligible post-scan image retention (called simply image retention hereafter) characteristics _____ which make its dynamic characteristics superior to conventional vidicon tubes. As in the vidicon, an electron beam is directed at, and deflected (in a regular video raster) over, the back surface of the target rendering it negatively charged. This surface is charged less negatively in proportion to the amount and in spatial correspondence with the light falling on each site on its photoelectric front surface. As the reading electron beam sweeps the back surface of the target, it is repelled or attracted in proportion to the degree of charge (brightness) at each respective site on the target. If no light is falling on the target, there is a maximum negative charge on the back face of the target and practically all of the electron

beam is returned to the electron multiplier in the rear section of the tube. The less negative the charge at each site on the target, the fewer the number of electrons in the beam which are returned to the electron multiplier from this site on the target. Therefore, the magnitude of the difference between the number of electrons in the incident and returning electron beam of an image orthicon tube is proportional to the amount of light falling on the photoelectric surface site at which it is impinging. This phenomenon--the difference between incident and returning electron beam current being minimum when no light falls on the photoelectric surface and maximum when the photoelectric surface is fully illuminated--is responsible for the image orthicon's unusual characteristic of showing maximum noise in the black (nonilluminated) areas of the image and minimum noise (maximum signal-to-noise ratio) in the white (maximally illuminated) areas.

Image Isocon.--The image isocon camera is essentially a return beam tube similar to that of the image orthicon, but because the processing electron optics in the return beam path are more sophisticated, this camera achieves much improved operating characteristics. The video signal obtained is directly proportional to illumination, as in the vidicon. The noise characteristics, dynamic range, and sensitivity are also improved severalfold relative to the image orthicon. Were it not for the expense of manufacture, difficulty of operation, and the recent interest in silicon target vidicons, the isocon would probably be in greater use today.

Camera Characteristics and Roentgen Angiography

Conventional television cameras have three characteristics of special significance in relation to the temporal resolution capabilities of video angiography. They will be described under the following headings: (1) image integration and storage; (2) interlaced scanning; and (3) image retention.

Image Integration and Storage.--When any portion of the video camera target is illuminated for a fraction of a second, a photoelectric or conductive effect is built up (integrated) on the target in proportion to the intensity and duration of the period of illumination. The photoelectric effect (image) is stored as a distribution of electrical charge on the target and, if it is not read off by the scanning electron beam, this charge distribution tends to equalize laterally, smearing the image at a rate depending on the lateral conductivity of the target. Images can be stored on the target of an image orthicon and other tubes for 15 seconds or longer (3).

When operation of the x-ray source is continuous and a conventional interlaced scan television camera is used for video angiography, the integration and storage characteristics of the camera target result in exposure times equal to the time ($33 \frac{1}{3}$ msec) which elapses between successive scans of each particular site on the target. This long exposure time, which is inadequate for resolution of the position of rapidly moving objects, can be decreased by

using x-ray pulses of brief duration to transradiate the
the
object under study. However, /pulses (frequency, 60/sec;
duration, 1 to 4 msec) which are suitable for this purpose
must be synchronized to occur just prior to each vertical
scan of the video camera target.

The improvement in the temporal resolving capability
of a fluoroscopic image intensifier video camera chain
provided by pulsed operation of its x-ray source is illustrated
by photographs of stop-action single field replays from a
video disk of roentgen images of holes in a rapidly moving
lead plate (Fig. 3). The circular lead plate, which was
interposed in the roentgen beam near the face of the intensifier
tube, was spinning at 1 revolution per second (rps) during the
video disk recording. The discrete images of the circular
holes and the slit near the periphery of this plate (Fig. 3
right panel) were recorded during pulsed operation of the
x-ray source and can be compared with the blurred images
obtained during continuous operation of the same x-ray
source (Fig. 3 left panel). It should be pointed out that
these images were obtained during noninterlaced operation
of the video camera. This mode of operation reduces the
scanning interval of the raster of successive video fields
from 1/30 to 1/60 second. Consequently, the image blurring
illustrated in Figure 3 is about 50% less than that which
would be produced by the doubling of the exposure time to
33 1/3 msec which pertains during continuous x-ray operation

and the interlaced mode of scanning used in conventional video cameras.

Interlaced Scanning.--The interlaced scanning mode of operation is used in conventional television to maximize the spatial resolution and to maintain a refresh rate of 60/sec on the display screen, a frequency which is much greater than the flicker-fusion characteristics of the human eye. The temporal and spatial composition of the (scanning pattern) horizontal video line raster/of a conventional video frame is illustrated in Figure 1.

As would be expected from the interlaced operation, the temporal sequence of successive horizontal lines differs from their vertical sequence. Consequently, the first line of the even field (horizontal line 2 in spatial [vertical] sequence) is actually line number 263 in temporal sequence--and so on down to the bottom of the raster where line 497 in spatial sequence is actually 249 temporally.

Due to the image storage characteristics of the target required for interlaced operation of conventional television cameras, the image information at each point across each successive horizontal line is stored and retained at its specific position on the video raster over the entire interval which elapses between successive vertical scans of this site on the video raster. This scanning interval, which the amounts to 1/30 second when/ conventional mode of interlaced

scanning is used, results in serious degradation of the temporal resolution capabilities of roentgen videograms even when pulsed operation of the x-ray source is used. This is illustrated in Figure 4 by photographs of stop-action single field replays of rapidly moving images obtained by the same system as used for Figure 3.

With 60/sec, 2-msec pulsed operation of the x-ray tube (Fig. 4 right panel), two full-intensity discrete images of each aperture in the lead plate are generated on the target during the interval ($1/30$ sec) which elapses between successive scans of either the odd or even fields of the video raster. These adjacent images are separated by the distances their respective sites on the spinning lead plate moved during the interval ($16 \frac{2}{3}$ msec) between successive x-ray pulses. In spite of the fact that the individual images making up each image pair were generated at successive $1/60$ -second intervals in time, they are "read off" the target and displayed simultaneously during each successive $1/30$ -second scan of either the odd or even fields of a conventional interlaced video raster. The progressively dimmer successive image pairs in the counterclockwise direction from the full-intensity pairs are the residual images retained ("sticking") at the particular sites on the target which the light spots were traversing at instants $3/60$, $4/60$, and $5/60$ second, respectively, prior to the most recent (last) point in time at which the most clockwise positioned image was generated. The intensity of these

residual image pairs is determined by the image retention ("sticking") characteristics of the target of the video camera. The badly blurred images produced by continuous x-ray operation under these circumstances are shown in the left panel of Figure 4.

Image Retention.--As evident from Figures 3 and 4, a single sweep of the electron scanning beam over any particular site on the target of a video camera does not completely remove the photoelectric effect (image) at this site.

A quantitative measure of the degree of image retention after successive scans of the camera's target can be obtained by measuring the height of the video signals (in volts) from an oscilloscope display of single horizontal video lines obtained during stop-action replay, from a video disk, of a single video field such as shown in Figure 3 (right panel). The horizontal lines selected for measurement are the particular lines which cross approximately the midportions of the progressively dimmer displays produced by the repeated scans (1 to 5) of the successive counter-clockwise images of a particular aperture in the spinning lead plate.

A comparison of the image retention characteristic of four different television camera tubes determined by this technique is shown in Figure 5. Note that the high degree

of image retention of standard sensitive (antimony trisulphate) vidicon tubes makes them unsuitable for dynamic measurement purposes.

Figure 6 illustrates the degradation in temporal resolution of the roentgen silhouettes of a moving object due to the combined effects of interlaced operation and the image retention characteristics of the camera tube; it also shows the temporal relationships of the 60/sec imaging x-ray pulses used to improve temporal resolution and which must be synchronized with the interlaced odd and even fields of the video system.

Figure 6 requires a detailed explanation. The images generated by a roentgen television chain recording the silhouettes of an opaque arrow rotating at 6 rps are used to bring out the temporal resolution capabilities of a conventional video system. The vertical (spatial) sequence of the video lines of the successive odd and even fields used to record the images of this rotating arrow is shown (Fig. 6 top panel), along with its temporal relationship to the vertical blanking pulses, generated during successive vertical retraces of the video beam, preceding the vertical scan of each successive video field. The temporal relationship of these vertical blanking pulses to the x-ray pulses (frequency, 60/sec; duration 1 msec) used to produce the 60/sec images of the arrow is also indicated (Fig. 6 second tracing from top). The actual images generated by the first five

1-msec imaging pulses (A through E) are illustrated (Fig. 6 Successive circles at center); the relative intensities of the silhouettes of the rotating arrow are indicated by the thickness of the successive images. Also illustrated (Fig. 6 bottom panel) is a bar graph representation of the intensity of the images generated by the single x-ray pulse A residing on the target of the television camera at successive 60/sec instants just prior to each of the 10 successive vertical scans of the video beam after pulse A. The intensities of this initial image of the arrow regenerated during the first 5 successive scans of the odd fields are indicated by the shaded bars, and the intensities of this same image regenerated by the alternate scans of the 5 successive interlaced even fields are indicated by open bars plotted as a percentage of the initial, full intensity of the image residing on the target immediately after imaging pulse A.

Following x-ray pulse A, the first vertical sweep of the odd field generates a full-intensity image of the arrow in the position it occupied when this imaging pulse occurred. A second imaging pulse B occurring 1/60 second later generates a full-intensity image of the arrow on the video screen at its new position, separated by 36° from its initial position due to its rate of rotation (6 rps). As a result, when the even field is swept off, two full-intensity images of this arrow are generated showing its position at these

two successive 1-msec intervals in time separated by $1/60$ second. A third 1-msec imaging pulse then occurs $1/60$ second later. This results in two full-intensity images of the arrow on the odd positions of the raster of the video camera so that when the following sweep of the odd field occurs, three images of the arrow are generated (Fig. 6 center circle); the first, in the clockwise direction, is a dim image and the second and third the full-intensity images generated by imaging pulses B and C. The intensity of the residual image generated by x-ray pulse A is determined by the image retention characteristics of the particular video camera used. For this plot a post-single scan image retention of 5% was assumed.

A fourth 1-msec imaging pulse (D) then occurs $1/60$ second later, and the following (second) vertical sweep of the even field then generates two dim (residual) images of the arrow separated by 36° (since they were generated by imaging pulses A and B, both images of which have been swept once by the first and second even field scans respectively). These two dim images are followed by two full-intensity images of the arrow also separated by 36° (since they were generated by the two preceding image pulses C and D of the 60/sec pulse chain). This process then continues in successive fields for the duration of the recording.

It is evident from this diagram and the preceding figures that the temporal resolution of conventional video

systems, all of which use interlaced operation, is not adequate to record moving objects the speed and motion of which are appreciable during the periods of $1/30$ second elapsing between alternate vertical sweeps of the interlaced fields.

The obvious way to eliminate this defect in temporal resolution of conventional video systems is to devise a system which does not use interlaced operation, that is, to arrange the electronics and logic of the system so that the horizontal scan lines of successive video fields traverse exactly the same positions on the target of the video camera.

The spatial and temporal arrangement of the raster of such a noninterlaced system is shown schematically in Figure 7. In this arrangement the vertical (spatial) sequence of the horizontal lines of successive video fields is identical. Therefore the position of each respective horizontal line in the raster is identical in successive fields, as indicated by the identical numbers of the horizontal lines for the first and second fields (Fig. 7 left margin) and the position and the presence of only one set of solid horizontal lines. The temporal sequence of these lines, however, would be similar to that of the conventional interlaced system, the first field extending from line 1 to line number 249 while the temporal sequence of the second video field extends from approximately line 263 to number 511. The theoretical effect on the temporal resolution of the video

system with noninterlaced, as compared to conventional interlaced operation, is illustrated in Figure 8.

The format of Figure 8 is similar to that of Figure 6. The same roentgen television chain is used, the opaque arrow rotating between the x-ray source and the image intensifier tube at 6 rps. The vertical sequence of the video lines (in this instance, identical for the first and second video fields) is shown on the top line, the vertical blanking pulses being separated by the $1/60$ -second intervals indicated on this same line. The second line illustrates the 1-msec imaging x-ray pulses separated by intervals of $1/60$ second and occurring just prior to each vertical blanking pulse in the second line; and in the middle panel the reproductions of the face of the television monitor are drawn. The first imaging pulse A generates a full-intensity image of the arrow on field 1 and the amplitude of this signal is represented by the crosshatched bar A shown in the bottom panel. A second image (B) of the opaque arrow, separated by 36° from image A, is generated by the second 1-msec imaging pulse (B) occurring $1/60$ second later. This full-intensity image (field 2) is displayed simultaneously with a dim residual image of the arrow generated by pulse A, the diminished intensity of which is determined by the image retention characteristics of the particular video camera being used (Fig. 8 bottom panel, bar A'). The third imaging pulse C occurring another $1/60$ second

later generates a full-intensity image of the arrow at its correct temporal position on the video screen while two progressively dimmer residual images of the arrow in the counterclockwise direction are also displayed (field 3). The faintest image, which is at the position which pertained during imaging pulse A, is very dim--as determined by the degree of image retention present in the tube after two successive vertical scans. The second dim residual image is the image retention after one vertical scan of the image generated by x-ray pulse B.

The dramatic improvement in temporal resolution obtained by noninterlaced operation (indicated by comparing Figures 6 and 8) can be verified by pictures of stop-action single field displays of roentgen video images of a rapidly moving object, as shown in Figure 9. This figure also highlights the importance for dynamic studies of selecting camera tubes characterized by the least possible degree of image retention.

The inadequacy of conventional television systems for measuring dynamic changes in dimensions and determining changes in volume of solid objects (e.g., the left ventricle) therefrom can be demonstrated by using a roentgen opaque cube of known dimensions positioned at the intersection of the central axes of the respective orthogonal roentgen video systems of a biplane roentgen videometry assembly (2).

Biplane recordings of its silhouettes were obtained as the cube was rotated around a central orthogonal axis at ^{revolutions per minute} approximately 25/(rpm). The volume of the cube was calculated from its silhouettes at a rate of 60 values/sec during the period of rotation, assuming that the respective orthogonal silhouettes measured during rotation represented the true silhouettes of a rectangular object with its orthogonal surfaces oriented perpendicularly to the respective orthogonal roentgen beams.

The results of such a study are shown in Figure 10. At the onset of this plot the cube was stationary and its orthogonal surfaces oriented perpendicularly to the two roentgen beams. During this period, the calculated volume of the cube agreed perfectly with its actual volume of 93 ml. The cube was then rotated around its central axis at a variable rate and, as expected from geometric considerations, as the area of the orthogonal silhouettes increased while the cube became increasingly more diagonally oriented in relation to the orthogonal roentgen beams, the calculated volumes increased progressively; when its diagonals were perpendicular to the roentgen beams, the volume reached a maximal value of 186 ml--exactly twice its actual volume as predicted from the geometry involved. With continued rotation of the cube the calculated volume values decreased progressively as anticipated; however, the minimum value for the calculated

volume was significantly greater (by approximately 20%) than the actual volume of the cube, which should have been calculated correctly at the instant in time when its surfaces were oriented perpendicularly in relation to the roentgen beams.* As the rotation continued progressively more slowly the calculated volume values again increased progressively to the theoretically expected maximum value of twice the actual volume of the cube; they then decreased again to a minimum value which, however, at this slower speed diverged less from the true expected value than did the minimum value obtained when the cube was rotating faster.

The superiority in temporal resolution provided by noninterlaced as compared to interlaced operation is illustrated by the computer-generated plot shown in Figure 11. The format of this figure is identical to the plot shown in Figure 10. The volume values calculated by the computer for interlaced (Fig. 11 open circles) and noninterlaced operation (Fig. 11 solid circles) were identical when the cube was stationary and corresponded with the actual volume of the cube of 93 ml as expected. As rotation of the cube moved

*At 25 rpm, the maximum error due to 60/sec sampling alone is less than 5% of the correct volume of the cube.

into a more diagonal position in relation to the orthogonal roentgen video systems, the values obtained by the noninterlaced and the interlaced system remained superimposed as long as the areas of the orthogonal silhouettes on the respective biplane video rasters were increasing up to the theoretically expected maximum value of 186 ml, twice the actual volume of the cube. However, when the cube began to rotate back toward its true orthogonal position in relation to the biplane systems--so that the areas of its two silhouettes on the biplane rasters were decreasing progressively--the calculated volumes from the interlaced values were systematically less than those of the noninterlaced values. The noninterlaced values decreased to a minimum value equal to the true volume of the cube at the instant when the cube was oriented so that its orthogonal surfaces were perpendicular to the roentgen beams of the biplane system. The minimum value obtained by the interlaced system at this instant, however, overestimated the true volume of the cube by more than 30%.

In the next phase of rotation, the calculated volume values again became identical during the period of increasing areas of the silhouettes of the cube on the respective video camera rasters up to the instant when the cube was exactly diagonally oriented in relation to the orthogonal roentgen beams. The two values diverged again during the period of decreasing area of the

silhouettes; however, as the rotation slowed down, the magnitude of the overestimations by the interlaced system decreased in almost direct proportion to the slowdown in the rate of rotation of the cube.

The inferior temporal resolution of conventional interlaced television systems in delineation of the silhouettes of moving objects illustrated by Figure 11 explains the fact that stroke volumes, measured as the difference between left ventricular end-diastolic and end-systolic volumes determined by biplane roentgen videometry using an interlaced system, are systematically less than the values recorded simultaneously by an accepted independent method (electromagnetic flowmeter) (4), as illustrated in Figure 12. During the period of systolic contraction when the area of the ventricular silhouettes is decreasing rapidly as blood is ejected into the aorta, the image storage characteristics of the interlaced camera tube ⁱⁿ cause a lag (1/30 second)/the images being read off by each successive video scan. Therefore, the rapidly decreasing areas of the ventricular silhouettes during systole are systematically overestimated, since the area displayed during each vertical scan is actually the area which was present 1/30 second prior to the instants of the successive scans.

The practical importance of the inferior temporal resolution of conventional television systems for use in left ventricular angiography has been demonstrated by comparing

replicate stroke volume values determined in close temporal sequence using interlaced and noninterlaced operation of the video camera (Table). Interlaced operation gave average stroke volume values which ranged from 2.5 to 35% larger than values obtained in close temporal sequence using noninterlaced operation.

Discussion

The conventional interlaced scan mode of reading off the image stored on the light sensing target of a television camera restricts sampling of image information impinging at a specific site on the camera target to a rate of 30 samples per second. Doubling of this sampling rate by using noninterlaced scanning gives adequate temporal resolution of the dynamic aspects of angiographic data providing that the aperture (exposure) time of each sample is short enough to "freeze" the motion of the most rapidly moving elements of the images under study (5). The required very short exposure times can be obtained by pulsed operation of the x-ray source using x-ray pulses of 1 to 4 msec in duration, as illustrated in Figure 8.

Given these modes of operation, the degree of temporal resolution attainable by a roentgen video system is determined ultimately by the image retention "stickiness" characteristics of the target of the video camera. Ideally the image information residing on the scanned raster of the target should be completely read off by a single scan.

Although this ideal is not yet technologically attainable, it is important that camera tubes with the minimum possible image retention characteristics be selected for video angiographic purposes. As illustrated in Figure 5, the best available cameras in this respect show a residual image after a single scan of about 5% of original intensity.

In the dynamic situation, a sizable error in the estimate of changes in the amount of contrast material determined by roentgen videodensitometry can result if the image retention characteristic of the particular television camera used is large. Since the charging and discharging characteristics in response to incident illumination of various types of target materials are not strictly linear, the interrelationship between the illumination intensity at any instant in time and the resulting concurrent video signal is complex and, therefore, difficult to calculate. Due to this analytic complexity, actual measurements of possible errors of this type should be carried out on the video camera component of any system under conditions which duplicate those in which it is to be used as a measuring instrument. In general, however, the error is negligible if either the image retention of the target or the change in illumination intensity for a period of $1/60$ second is small.

For cameras with appreciable image retention, it would be expected that a rapid decrease in target illumination

would result in an overestimation of the illumination of the target at any instant in time and, conversely, an underestimate of target illumination would occur during periods of a rapid increase in illumination.

Noninterlaced operation of a video camera, although providing an important increase in its temporal resolution capabilities, entails a loss in spatial resolution in the vertical axis if the usual ratio (4:3) of horizontal-to-vertical dimensions of the video image raster is maintained. Decreasing the vertical sweep speed by 50% will restore the normal degree of vertical resolution (i.e., horizontal lines per inch) at the expense of reducing by 50% the maximum vertical dimension of the image which can be displayed. Since, in our experience, 250 horizontal lines are sufficient to display the full vertical extent of even enlarged human hearts, this is not a serious disadvantage, at least for left ventricular angiography.

Acknowledgment

The authors are indebted to Mr. Merrill A. Wondrow for his help with the biplane video chain, Mr. Don I. Erdman for fabrication of the rotatable cube and lead disk, and Mrs. Jean Frank and her co-workers for the manuscript preparation and illustrations.

Comparison of Stroke Volume Values Calculated From Sequential Left Ventricular Video Roentgenograms Recorded Using Noninterlaced (NIL) and Interlaced (IL) Scanning of Video Camera*

Television camera sweep mode	Left ventricular stroke volume, ml†	Left ventricular pressure, mm Hg†		No. beats analyzed	Difference in calculated stroke volume, %
		End-diastolic	Systolic		
NIL	15.7 (0.8)	5.5 (0.5)	115.4 (1.9)	20	
IL	13.1 (0.7)	5.3 (0.4)	113.6 (1.5)	21	17
NIL	14.0 (0.7)	5.5 (1.5)	115.2 (1.3)	22	
IL	12.9 (0.5)	5.5 (1.4)	114.4 (1.1)	22	8
NIL	12.4 (0.2)	5.7 (0.2)	117.0 (0.1)	24	
IL	12.1 (0.1)	5.8 (0.3)	119.0 (0.3)	25	2.5
NIL	14.1 (1.2)	5.1 (0.2)	88.1 (2.1)	20	
IL	12.2 (0.8)	5.2 (0.2)	85.7 (0.2)	17	13
NIL	11.1 (1.4)	5.0 (0.2)	88.8 (2.3)	20	
IL	7.2 (0.5)	5.3 (0.1)	85.9 (0.3)	17	35

*Data from dog, anesthetized with morphine and pentobarbital sodium; constant heart rate of 80 beats/min obtained by electrical pacing of right atrium.

†Mean values (and SEM).

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Legends

Fig. 1. Vertical and temporal sequence of horizontal scanning lines used in conventional interlaced mode of operation of television cameras. Dashed and solid lines represent spatial arrangement of vertical raster of horizontal lines forming respective odd and even fields of single interlaced video frame. (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp 1. By permission.)

Fig. 2. Diagram of voltage variations of video electron beam (video signal) during production of single horizontal line of television image. A, Synchronizing voltage pulse, for alignment of successive horizontal video lines. B, Ground potential, the reference level to which the video signal is "clamped" at the onset of each horizontal line. (Special circuitry to "hard clamp" onset of each video line to fixed reference voltage is required for use of television system for quantitative measurement.) C, Pedestal, or voltage output of video camera when no light is falling on its input phosphor, i.e., "black level." D and F, Voltage level of peak video signal, which represents maximum brightness of video image, is adjusted to about 0.7 v to obtain maximum gray level range (sensitivity) for image under study. E, Difference between voltage of video signal at B and E is proportional to difference in incident light intensities at these two sites on camera target where this particular horizontal scan line has swept its surface.

Fig. 3. Comparative resolution of moving roentgen silhouettes by image intensifier video system using continuous (Left Panel) or 60/sec 2-msec (Right Panel) x-ray pulses. Photographs of television screen during stop-action single field replays from a video disk of holes (bright spots) at the periphery of a circular lead plate spinning in clockwise direction at about 1 rps; lead oxide vidicon (plumbicon) camera with noninterlaced scanning was used. Note blurring of images (Left Panel) due to continuous exposure of camera's light sensing target caused by continuous operation of x-ray source during each 16 2/3-msec scan interval.

Fig. 4. Comparative resolution of moving roentgen silhouettes by image intensifier-video system using continuous (Left Panel) or 60/sec, 2-msec (Right Panel) x-ray pulses and conventional interlaced scanning of plumbicon video camera. Note double image pairs (Right Panel), the counter-clockwise member of which is displayed 1/60 second late, due to interlaced mode of operation of video camera. For further details, see legend of Figure 1 and text.

Fig. 5. Comparison of image retention (sticking) ^{camera pickup} characteristics of different video/ tubes. Note that single sweep of electron scanning beam of video camera does not remove all charge (image) residing on its target. This image retention characteristic, if large as in standard vidicon, degrades resolution of rapidly moving objects such as ventricular borders during systole.

Fig. 6. Schema of effects of interlaced scanning and image retention characteristics of television camera on temporal resolution of moving roentgen silhouettes by image intensifier video system. Successive silhouettes of opaque arrow rotating at 6 rps, generated by 60/sec, 1-msec x-ray pulses sensed on a fluoroscopic image intensifier (I) and displayed via television camera (TC) television monitor (VM) chain, are illustrated. Note similarity between schematic multiple video images of the arrow (Right Center) and multiple images in an actual photograph of video screen (Fig. 4 Right Panel). For further details, see text. (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp 1. By permission.)

Fig. 7. Vertical and temporal sequence of horizontal scanning lines for noninterlaced mode of operation to improve temporal resolution of television cameras. Electronic control circuits are altered so that camera scanning beam traverses identical raster on target for successive video fields; consequently, if pulsed operation is used, exposure time for each video field is determined by duration of the imaging pulses. In this situation image retention characteristic of video camera is an important determinant of temporal resolution of images of

moving objects (as illustrated in Fig. 8). (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp 1. By permission.)

Fig. 8. Schema of the effects of image retention characteristics of television camera on temporal resolution of moving roentgen silhouettes by image intensifier video system using noninterlaced operation. (For definition of symbols see legend of Fig. 6.) Image produced by each 1-msec x-ray pulse is read off (displayed) immediately by vertical scan which follows this pulse. Since positions of successive vertical scan rasters on the target are identical, maximal period during which image information can be stored on this raster is 1/60 second. When pulsed operation is used, exposure time for each field is determined by duration of imaging pulse so that discrete fill-intensity images of arrow (A-D) are displayed in successive video fields (1-5) (circular reproductions of the video screen in the central portion of the figure). Intensities of dim images (A' and A'') are determined by amount of residual image remaining on raster of camera target after first (A') and second (A'') raster scans, respectively. Note similarity between these schematic video images and those in photograph of a video

screen obtained under similar conditions (Fig. 9 Right Panel).

For further details, see text. (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp 1. By permission.)

Fig. 9. Comparative resolution of moving roentgen silhouettes by image-intensifier video system using interlaced and noninterlaced scanning of plumbicon video camera and 60/sec, 2-msec x-ray pulses. Note that only full-intensity image generated by immediately preceding x-ray pulse was displayed when noninterlaced scanning was used. Intensity of residual progressively dimmer images in counterclockwise direction is determined by image retention characteristics of input phosphor of video camera (as illustrated in Fig. 8).

Fig. 10. Variation in calculated volume of a cube from its orthogonal roentgen video silhouettes recorded 60 times/sec during its rotation about orthogonal axis. Note that (1) during period S (cube stationary and orthogonally oriented in relation to roentgen beams) values calculated from its biplane silhouettes agreed with its actual volume; however, (2) when cube was rotating, due to poor temporal

resolution of silhouettes of moving object by television cameras using interlaced scanning, equivalent volume values, calculated at instants when cube was oriented or normal to roentgen beams, overestimated actual volume by amount varying directly with speed of rotation. (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp.1. By permission.)

Fig. 11. Illustration of errors in calculated volume of cube from orthogonal roentgen video silhouettes recorded 60 times/sec with and without interlaced operation of video camera. For discussion, see legend of Figure 10 and text. (From Wood EH, Ritman EL, Sturm RE, et al: The problem of determination of the roentgen density, dimensions and shape of homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology. In Proceedings of the 1972 San Diego Biomedical Symposium. Edited by N Silverman, 1972, pp 1. By permission.)

Fig. 12. Comparison of simultaneous stroke volume values determined by biplane roentgen videometry and by an electromagnetic flowmeter on ascending aorta in dog (anesthetized with morphine and pentobarbital sodium and studied without thoracotomy). Aortic flowmeter was calibrated in vivo on basis of determinations of cardiac output from

dilution curves of indocyanine green and simultaneously recorded aortic flow pulses. Note that although there is a close correlation between the stroke volumes for the same heart beats determined by these two independent methods, average flowmeter values are approximately 17% greater than those determined by videometry. This systematic error is believed due to inadequate temporal resolution of television cameras when conventional interlaced scanning mode of operation is used (as illustrated in Fig. 10 and 11). (From Ritman EL, Sturm E, Wood EH: A biplane roentgen videometry system for dynamic (60/second) studies of the shape and size of circulatory structures, particularly the left ventricle. In Roentgen-, Cine- and Videodensitometry: Fundamentals and Applications for Blood Flow and Heart Volume Determination. Edited by PH Heintzen. Stuttgart, Georg Thieme Verlag KG, 1971, pp 179-211. By permission.)

• DIAGRAM OF VERTICAL AND TEMPORAL SEQUENCE OF HORIZONTAL SCAN LINES FOR CONVENTIONAL (Interlaced) OPERATION OF A TELEVISION CAMERA

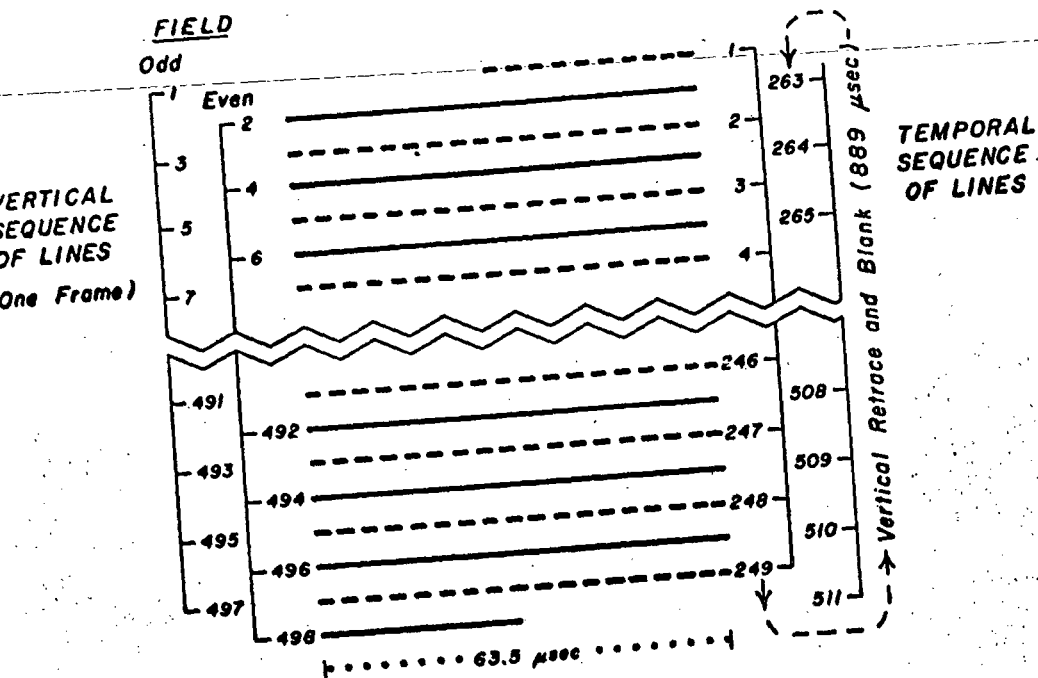


Fig 1

SCILLOSCOPE DISPLAY OF VOLTAGE (Video Signal) FROM A SINGLE HORIZONTAL VIDEO LINE

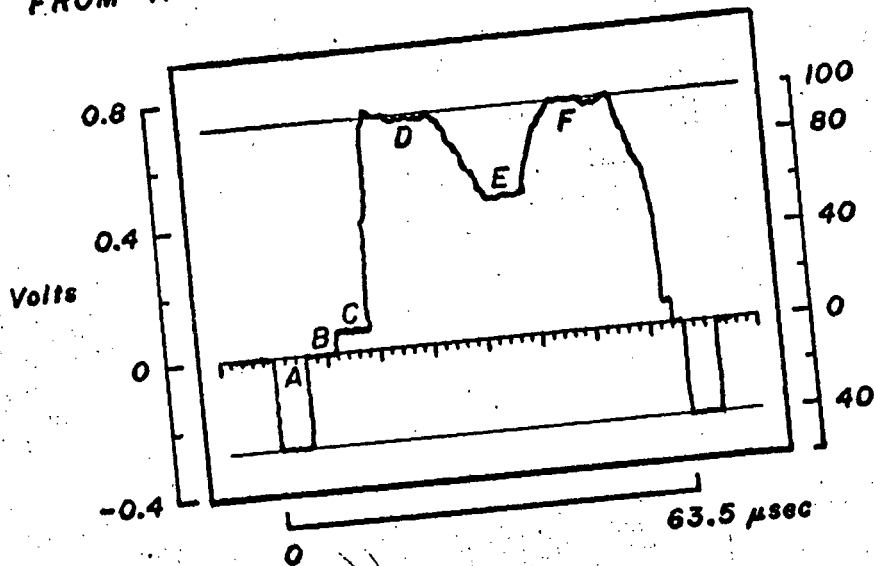
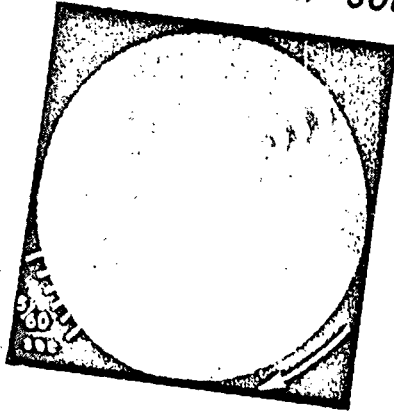


Fig 2

COMPARATIVE RESOLUTION OF MOVING ROENTGEN
SILHOUETTES BY IMAGE INTENSIFIER-VIDEO SYSTEM
USING CONTINUOUS OR 60/second 2-msec X-RAY PULSES
(Lead Oxide Vidicon Camera, Noninterlaced Operation)

CONTINUOUS X-RAY SOURCE



PULSED X-RAY SOURCE

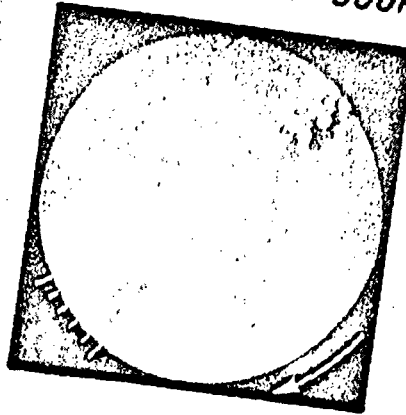
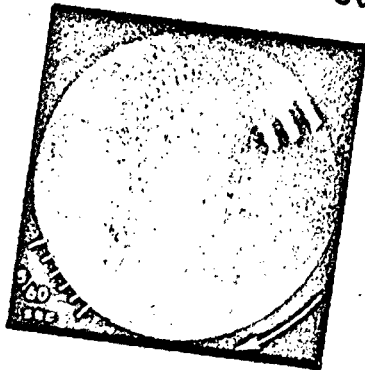


Fig 3

COMPARATIVE RESOLUTION OF MOVING ROENTGEN
SILHOUETTES BY IMAGE INTENSIFIER-VIDEO SYSTEM
USING CONTINUOUS OR 60/second 2-msec X-RAY PULSES
(Lead Oxide Vidicon Camera, Interlaced Operation)

CONTINUOUS X-RAY SOURCE



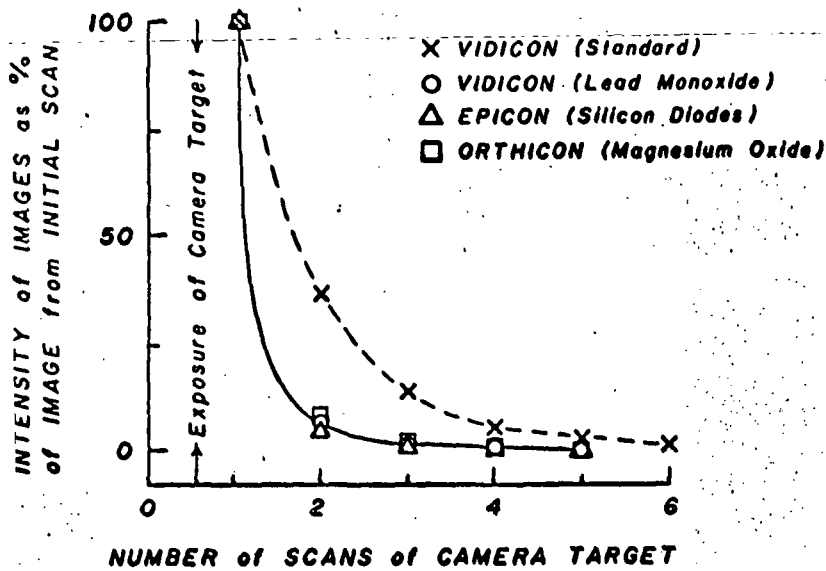
PULSED X-RAY SOURCE



Fig 4

IMAGE RETENTION (Sticking) AFTER SUCCESSIVE SCANS OF CAMERA TARGET

Comparison Different Video Cameras



SCHEMATIC OF EFFECTS OF INTERLACE AND IMAGE STORAGE CHARACTERISTICS OF TELEVISION CAMERA ON TEMPORAL RESOLUTION OF IMAGES OF A MOVING OBJECT

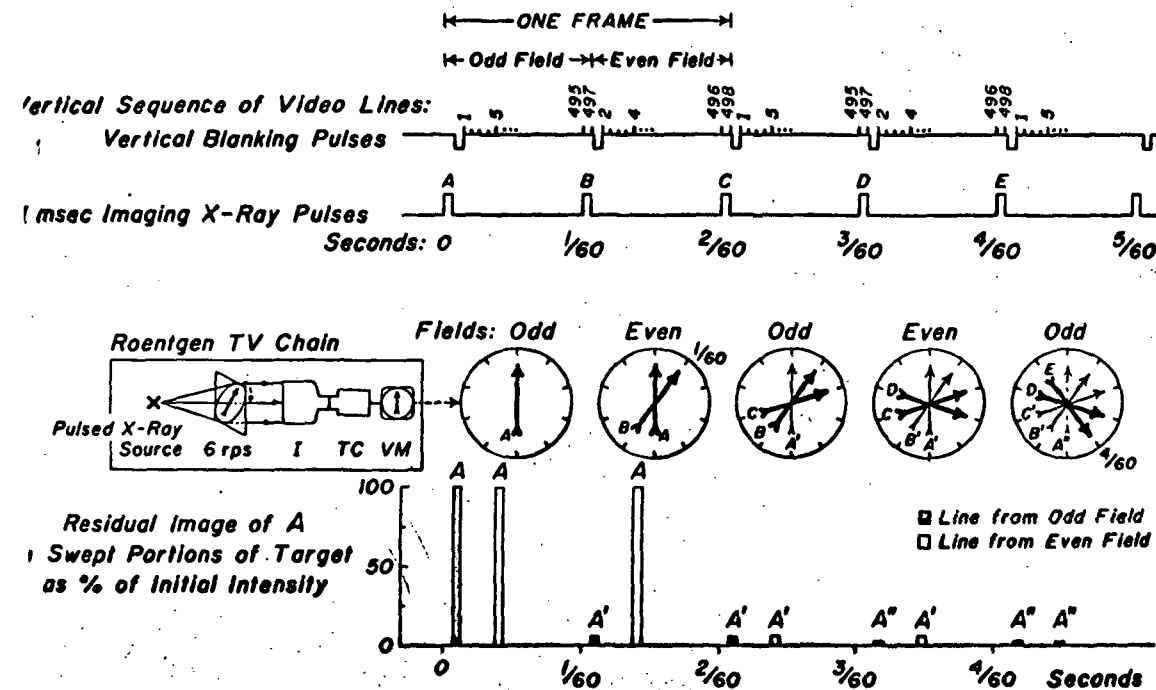
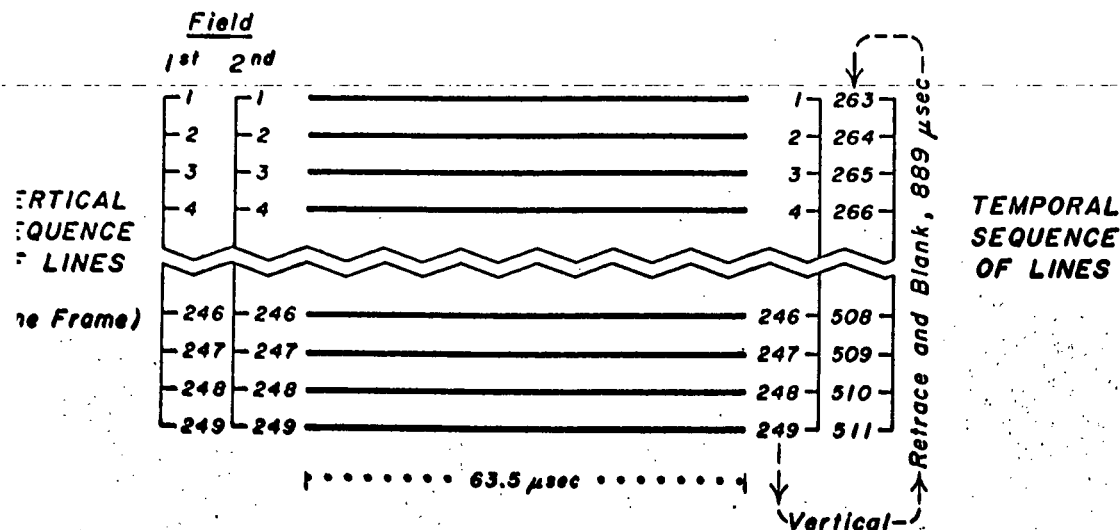
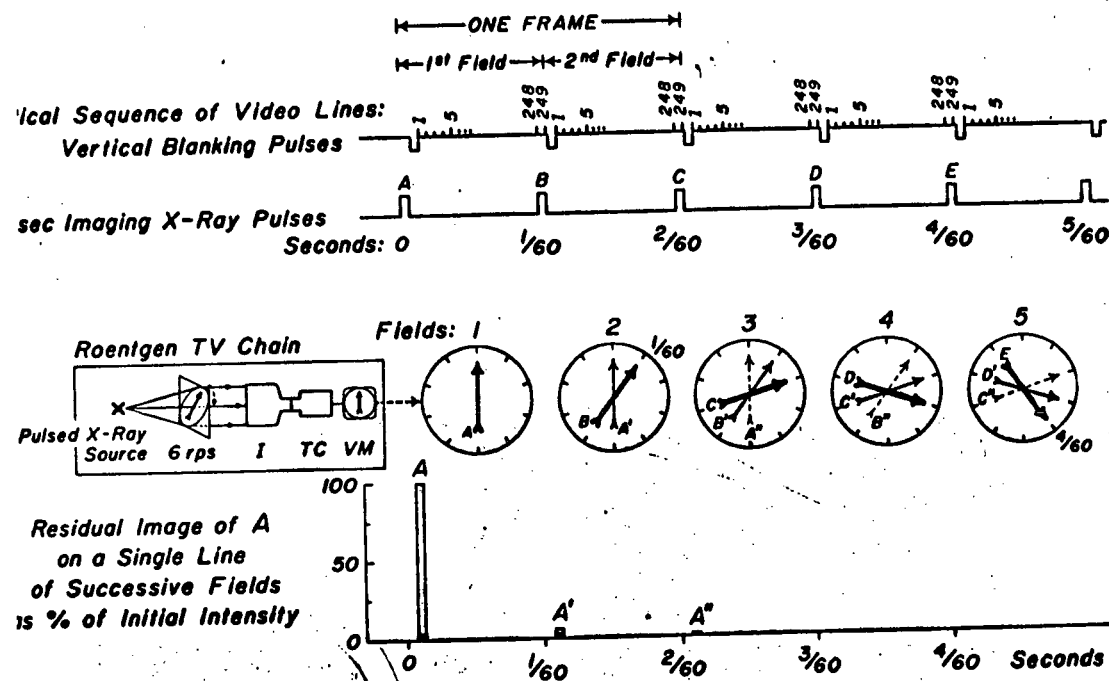


DIAGRAM OF VERTICAL AND TEMPORAL SEQUENCE OF HORIZONTAL SCAN LINES FOR NON-INTERLACED OPERATION OF A TELEVISION CAMERA

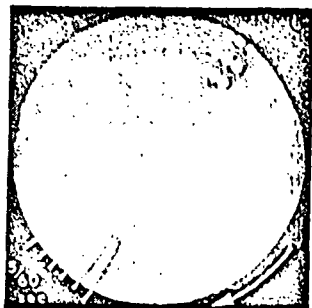


SCHEMATIC OF EFFECTS OF IMAGE STICKING CHARACTERISTICS OF A TELEVISION CAMERA ON TEMPORAL RESOLUTION OF IMAGES OF A MOVING OBJECT USING NON-INTERLACED OPERATION



COMPARATIVE RESOLUTION OF MOVING ROENTGEN SILHOUETTES
BY IMAGE INTENSIFIER-VIDEO SYSTEM WITH INTERLACED
AND NONINTERLACED SCANNING OF LEAD OXIDE
VIDICON CAMERA AND 60/second 2-msec EXPOSURES
(X-ray Source: 2-msec Pulses)

INTERLACED SCAN



NONINTERLACED SCAN



Fig 9

VARIATION IN CALCULATED VOLUME OF A CUBE
FROM ORTHOGONAL ROENTGEN VIDEO SILHOUETTES
CORDED 60 TIMES per SECOND DURING ITS ROTATION
ABOUT AN ORTHOGONAL AXIS

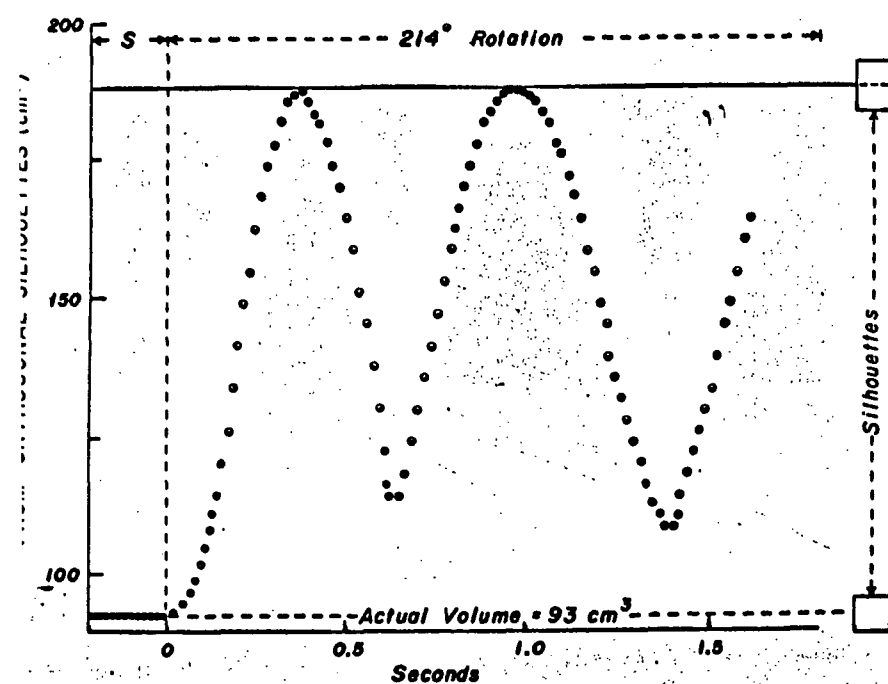


Fig 10

ILLUSTRATION OF ERRORS IN CALCULATED VOLUME OF A CUBE FROM ORTHOGONAL ROENTGEN VIDEO SILHOUETTES RECORDED 60 TIMES per SECOND WITH AND WITHOUT INTERLACE OPERATION OF A TELEVISION CAMERA

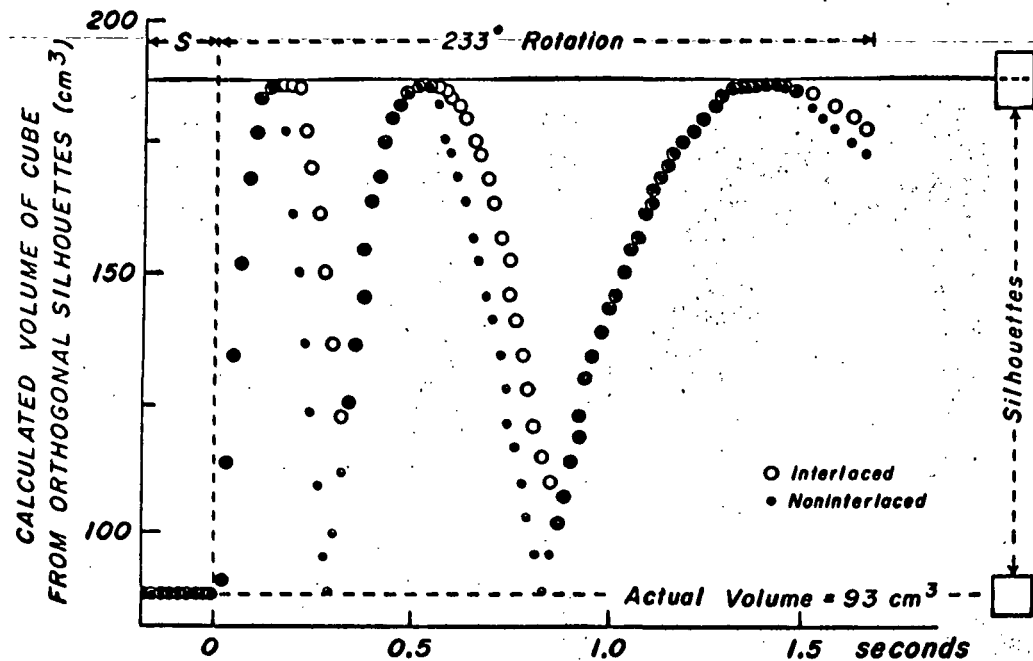


Fig 9

SIMULTANEOUS STROKE VOLUMES
(Dog 13.5 kg)

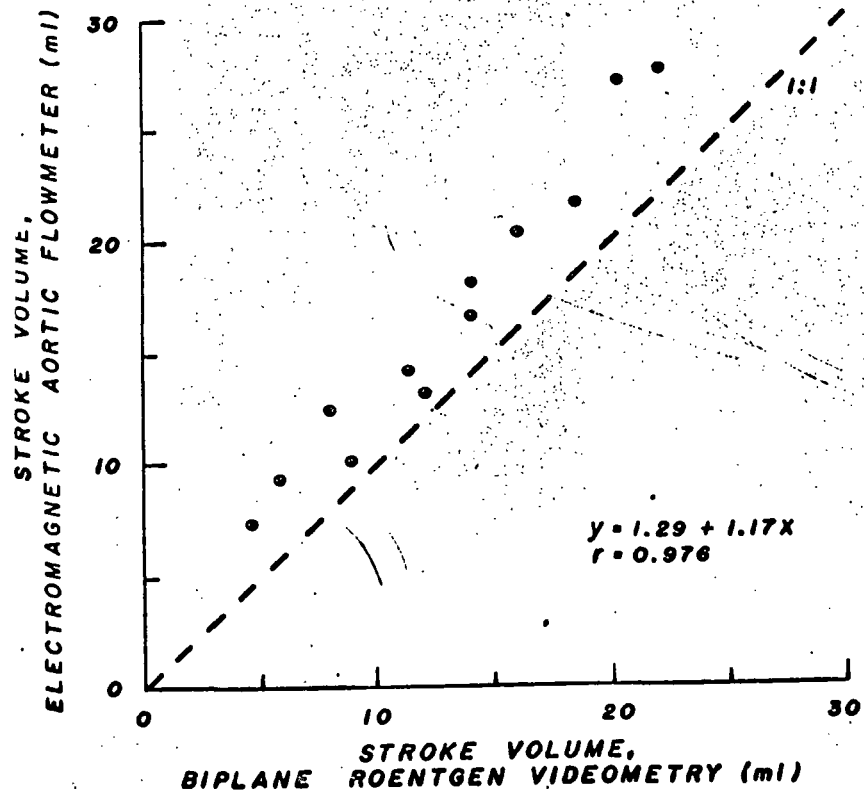


Fig 12

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Introduction

Many specific diagnoses of diseases of the heart can be obtained in cardiac catheterization laboratories. Dynamic changes in volume and distributions of coronary blood flow are studied by means of injecting roentgen-opaque (i.e., x-ray dense) material into the left ventricle or the right ventricle through a catheter whose tip has been threaded into the heart via a puncture in a peripheral vein or artery such as femoral artery in the leg. At the time of the injection of contrast media, the chest of the patient is irradiated with x-ray and dynamic movements of the opacified heart are projected onto a fluoroscopic screen and then recorded on videotape by a television system or on film by a photographic system. Although cine roentgenography (that using film) can have higher spatial and temporal resolution (Ref. 1) than video roentgenography (that using television), the cine systems require a longer time to complete the diagnosis since the film must be developed.

It has recently been shown that monoplane projections of the dynamic movements of the roentgenographic silhouette of the heart do not provide enough data to accurately characterize various diagnostic parameters, such as volume and geometry of the chamber (Ref. 2). Our laboratory has recently installed a biplane roentgenographic video system which has the capability of recording pairs of orthogonal video images of the heart on videotape at a rate of one pair of images every 1/60th second (Ref. 10). Computer analysis of these images is accomplished by transferring the videotape record to a video disc recorder for variable time-base (slow-motion, stop-action, reverse etc.) display and quantization. A combination of analog and digital analysis of these data is then used to obtain information concerning the state of the heart.

The purposes of this paper are 1) to describe the data acquisition system, 2) to

describe computer analysis of the data, and 3) to illustrate various formats of computer-generated displays of processed data obtained from two biplane videometry systems operating in both clinical and research environments.

Data Acquisition

A schematic diagram of a biplane roentgenographic system is shown in Figure 1.

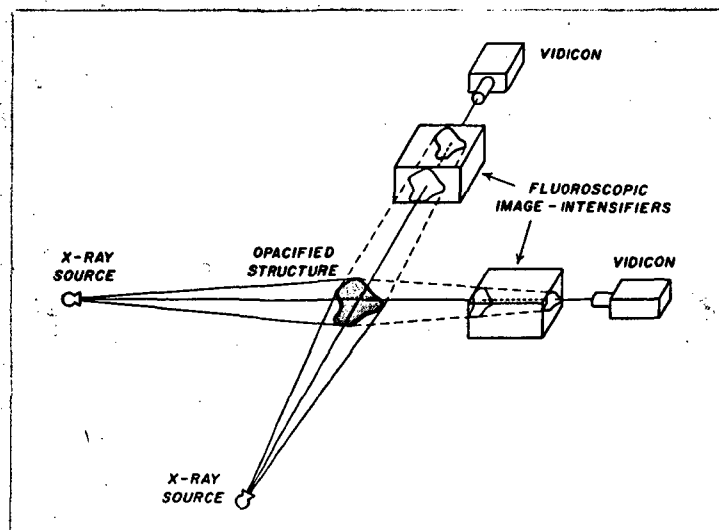


Figure 1. Schematic of an orthogonal biplane video roentgenographic system. Each x-ray source projects the silhouette of a roentgen-opaque structure onto a fluoroscopic screen is intensified for viewing by a vidicon camera. In this way, low levels of x-ray can be used. The two systems are sequentially pulsed 60 times per second for a period of 2 msec/pulse. While one source is on the image intensifier for the other source is blanked off, thus scattering x-rays are not recorded by the image system of the x-ray source which is off. Both cameras are swept in sync and the two x-ray sources are pulsed 5 msec apart during vertical blank. Each pulse of x-ray results in a charge distribution on the target of the vidicon which is proportional to the x-ray intensity

which impinges on the fluoroscopic screen. This charge is held until it is destructively read by the sweeping beam of the vidicon tube. Sixty images per second, each image having about 250 horizontal lines, are obtained by superimposing the raster scan sweeps of the vidicon target rather than interlaced scanning as used in standard television systems.

The axes of the two x-ray systems are orthogonal to one another. Each system has a fluoroscopic screen, an image-intensifier, and a lead oxide vidicon television camera. The two x-ray sources are pulsed at a rate of 60 times per second for a pulse duration of 2 msec. The two sources are pulsed sequentially during vertical blanking, one just prior to vertical retrace and the other just following vertical retrace. During the 2 msec that one source is emitting x-rays, the image-intensifier for the other source is blanked so that scattered x-rays do not generate an image on the target of its associate vidicon during this period. A like procedure is accomplished during the time the other source is on. The roentgen shadow cast by the active x-ray source is changed to light by the fluoroscope and intensified and stored on the target of the vidicon as a charge density distribution. This charge distribution remains on the target until the reading beam of the vidicon sweeps off the charge in a raster scan thus generating a video signal. This scan takes 16 msec, the time of one video field, and both images are swept simultaneously by the respective vidicon cameras.

The fluoroscopic image which is projected onto the target of the vidicon is swept by about 250 lines per field while the horizontal resolution is defined by the band-width of the video amplifiers and is greater than the 250 line vertical resolution. Standard television systems are such that the two fields making up a frame are interlaced so the set of horizontal lines of the first field in the frame lie between the lines of the subsequent field. However, in order to obtain true 2 msec roentgen exposures for each 60/second video field, this system has been modified in such a way that the sequential pairs of 250 horizontal lines contained in each frame are not interlaced, but are exactly superimposed upon each other. Consequently, the image generated by each sequential 2 msec roentgen pulse is destructively read-off prior to the occurrence of the next imaging pulse in the 60-per-second chain. Therefore, this system

obtains orthogonal projections of the trans-irradiated space 60 times each second.

To facilitate recording of the two vidicon camera signals representing the video images of each pair of orthogonal roentgen silhouettes, the sync signals for each camera are electronically delayed in such a way that the central portions of each video field are mixed together to form a single split-screen field containing both images. These video signals are recorded on a videotape recorder through a processor which allows simultaneous recording of analog signals such as left ventricular pressure, ECG, and the rate and volume of injection of the radiopaque contrast medium. This processor records the analog signals by amplitude modulating the first two microseconds of signal in each horizontal line. The analog signals are multiplexed onto the video lines repeating a sample of each signal every 17 lines allowing the recording of up to 16 analog signals, each sampled at a rate of about 1,000 per second (horizontal line rate is 15,750 hertz).

Although much information can be obtained from analyzing the distribution of densities of the silhouettes (Ref. 3), this paper will be concerned with the analysis of borders of the silhouettes (Ref. 4). Measurement of the borders of the silhouette is called videometry, while the measurement of density of small areas of the video picture is called videodensitometry.

The biplane roentgen videoangiographic system is shown in Figure 2 and depicts the alignment for calibration by using a rubber sphere of known diameter. The sphere is positioned at the intersection of the axes of the biplane system. This procedure is required to determine and correct image amplifications and distortions.

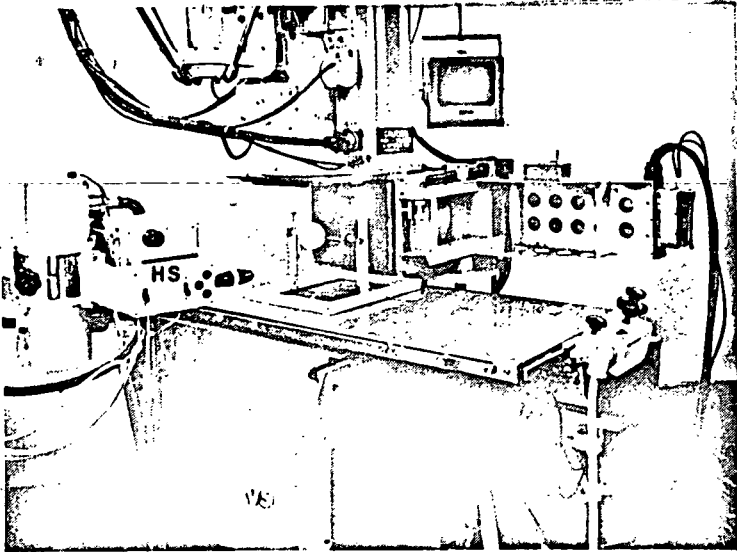


Figure 2. A biplane roentgen image-intensifier system as set up for calibration with a radiopaque ball of known diameter. The ball is centered at the intersection of the axes of the biplane video roentgenograph assemblies for the horizontal (source at HS, intensifier at HI) and vertical (source at VS in table support, intensifier at VI) systems. Since the diameter of the sphere is accurately known, image data obtained from the system can be transformed to correct for amplifications and distortions of the system calculated from recorded images of the sphere.

Figure 3 is a biplane video picture of the opacified left ventricle of a human. The horizontally striped bar on the left is the section of the picture used for the multiplexed amplitude modulation recording of the analog signals. The two silhouettes are the orthogonal silhouettes of the roentgen opacified left ventricle.



Figure 3. A photograph of a television monitor containing orthogonal biplane images of the roentgen opacified left ventricular chamber of a human. The video signals from the two orthogonal vidicon cameras are delayed such that one appears on the left-hand side and the other on the right-hand side of the video screen. In this way biplane images relating to identical points in time can be recorded simultaneously. The vertical bar with horizontal stripes on the left-hand side of the image represents the amplitude modulated portion of the signal used to record analog signals, such as left ventricular pressure, electrocardiograph, etc. Sixty such images are obtained each second by the method described in Figure 1

The positions in time (space) of the four border points encountered by each video line traversing the two silhouettes of the ventricle are determined by comparison of the video signal of each representative line with an operator-interactive level detecting circuit (Ref. 11). This circuit which generates isoroentgen density contours on the television monitor, as shown in Figure 4, is used to obtain contours of the silhouettes. Errors in border recognition caused by intervening ribs or the injection catheter, or by the unopacified blood entering the ventricular chamber during each period of filling are removed with a flying-spot video transmission scanner. This device allows the operator, using a pencil or eraser, to increase or decrease, respectively, the opacity of a sheet of translucent plastic film being scanned by a flying-spot scanner. The scanner generates a television signal representing a shaded "mask" which is added to the original video image, allowing the operator to change and control the intensity of the video signal being sensed by the border detection circuitry. Interactive manipulation of the video quantizer and flying-spot scanner devices can be effectively used to accurately delineate the left ventricular borders.



Figure 4. Photograph of a television monitor upon which is displayed the split-screen presentation of the same orthogonal bi-plane images of the human left ventricle pictures in Figure 3, except with the outlines of the two images brightened to represent the borders recognized by an operator-controlled voltage level sensing circuit. These borders may be interactively adjusted by adding various voltages to the original video signal using a flying-spot scanner assembly.

Digital Processing

Digital conversion of the signal representing the left ventricular outline is accomplished in the following way: at the time of the horizontal sync pulse, four 19-megahertz counters are started. The counters are stopped in sequence at the time the horizontal video line encounters the four recognized border points (two sides of each image). Thus the contents of each counter at the end of the horizontal line are proportional to the distance from a fixed reference point, the horizontal sync pulse, to each succeeding border recognition point. At the end of each horizontal video line, the contents of these counters are read by the computer (CDC 3500) through parallel digital lines. Each counter is read with an accuracy of 12 bits. The entire biplane borders of the object under study are digitized at the end of each field. This procedure results in a set of data for each video field containing four recognized border points for each of 100-200 video lines crossing the biplane roentgen shadow of the

object under study. Since there are 60 fields per second, this procedure yields a data array of about 50,000 data points in one second. In general, the contrast media is washed out of the ventricle in two or three heart cycles; therefore, the data acquisition is complete in about 3 seconds. Actual data acquisition time includes the shading procedure which is usually done for two points in the heart cycle: end-diastole, or the relaxed-filled state, and end-systole, or the contracted state. If the ventricular contours are defined by the operator for the images representing these two states, the borders can be automatically recognized by the quantizer for the images between these states and the image contours for the complete heart cycle can be digitized in real-time by playing the video disc recorder at full speed for the period under study.

Display and Analysis

After the data representing the borders of the object under study are transferred from the video disc to a digital tape using the videometry system, they are analyzed and displayed on a storage oscilloscope at a peripheral computer station (Ref. 12). Operator-interactive density contouring of the images and subsequent digitization of the defined outlines yields the computer display depicted in Figure 5. The digitized outlines of the images of the ventricular chambers are displayed for validation by the operator. Chamber volume was calculated to be 215 ml and the chamber pressure was 212 mm Hg.

There are two forms of data analysis, one resulting in computer-generated models of the structural and geometric form of the object under study and the other resulting in the derivation of parameters related to the function of the organ under study.

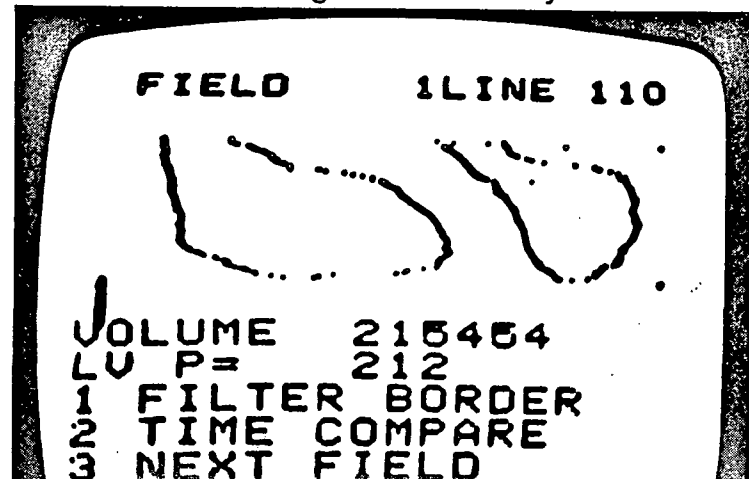


Figure 5. Computer-generated oscilloscopic output of videometry analysis program. The image borders for the biplane silhouettes pictured in Figures 3 and 4 are shown as recognized by the video quantizer and corrected for magnification and distortion upon digitization. The video field number on disc and the number of horizontal lines intercepted by the image are displayed above the contours. The calculated volume for the chamber at this point in the heart cycle was 215.45 ml of blood and the concomitant left ventricular pressure was 212 mm Hg. Four options for additional processing of the data or for new data analysis are indicated at the bottom of the oscilloscope.

Since the digitization process results in an outline of the object under study for only two orthogonal projections, various assumptions must be made in order to reconstruct and analyze the entire surface of the object. The following method of reconstruction of left ventricles is one used in this laboratory and has been extensively reviewed (Ref. 5).

It is assumed that the two orthogonal diameters measured from each of the 100-200 cross-sections of the ventricular chamber silhouettes are the major and minor axes of an elliptical disc representing the cross-section of the object at the level of each video line. A mathematical model for simulated three-dimensional oscilloscopic display was constructed from these elliptic discs by interpolating equispaced data points around their circumference and stacking the individual discs in order from top to bottom. The centers of the ellipses were aligned in space exactly as they occurred in the video images.

Figure 6 depicts such a model derived from data obtained from a roentgenographic study of an excised left ventricle of a dog.

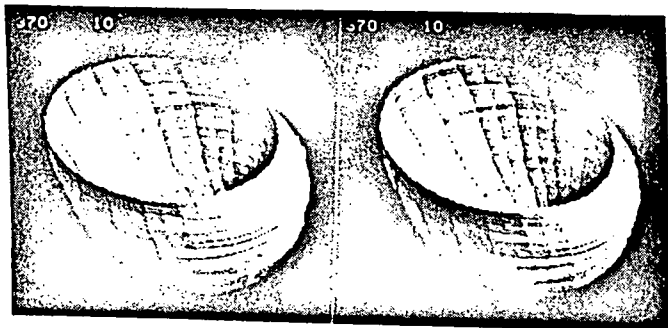


Figure 6. Computer-generated simulated three-dimensional (stereo) plot depicting surface of roentgen-opacified chamber of the left ventricle of a dog. Spatial dimensions were measured with biplane roentgenographic videometry system. Picture is time-exposure photograph of face of an oscilloscope and image is mosaic of 256 x 256 light spots. The orthogonal diameters and positions in space of the stack of approximately 50 elliptical discs making up the figure were obtained from orthogonal roentgen silhouettes of the ventricular chamber during play-back of record images from a video disc recorder. Three properties are illustrated which enhance the illusion of three dimensions: 1) the surface is solid; 2) shading is relative to a light source; and, 3) surfaces which are hidden are not plotted.

Techniques for computer generation of such simulated three-dimensional displays of surfaces have been described in detail elsewhere (Ref. 6,7,8). This figure is a time-exposure polaroid photograph of the face of an oscilloscope whose X-Y axes were driven by the computer. The image is made up of a mosaic of 256 x 256 points. The brightness of each point is modulated by varying its period of illumination. The illusion of three-dimensions is achieved by the combination of three characteristics. 1) The surface is continuous; although the data are known only at approximately 1600 points in space, linear spatial interpolation is used to fill in triangles resulting from the projection of triplets of neighboring data points onto the viewing plane (scope face). Thus the surface consists of flat triangular sections connected along their edges. The spots of the mosaic are close enough together to give an appearance of continuity when each spot of the mosaic falling within the triangle is illuminated. 2) The surface is shaded as if illuminated by a beam of parallel light rays; the brightness of each triangle depends on its orientation relative to a theoretical arbitrary illumination vector. The triangles are plotted brightly if they face the light vector and darkly if they are oriented orthogonal to the light vector. The light vector in Figure 6 is directed from the right at 45° and results in the body appearing as if it were illuminated by parallel light from that direction. 3) Hidden sections are not plotted; although the data for the entire surface are known, various hidden

portions of the surfaces should not be plotted. This is accomplished in two steps. First the triplets of data points for each surface triangle are plotted in sequence from nearest to farthest from the selected viewing plane (the theoretical position of the scope face), and the second each light spot on the mosaic is illuminated as a member of only one triangle. Thus portions of sections which are to be hidden are not added to the image.

Another type of display is that of a three-dimensional function representing parameters derived from the hemodynamic as well as structural data obtained from the roentgen opacification and video recording procedure. An example of such a parameter is the volume. $V(L,t)$ is a three-dimensional surface and may be derived from the videometry data in the following way. Assume that each cross-section measured by the horizontal line traversing the orthogonal biplane silhouettes of the image under consideration are elliptical. Then,

$$\Delta V_e = K * [(B_e + B_{e-1}) - (A_e + A_{e-1})] * [(D_e + D_{e-1}) - (C_e + C_{e-1})] / 16 \quad (\text{Eq 1})$$

in which, ΔV_e is the volume of the disc, K is the scaling factor incorporating the thickness of each cross-section, and $A, B, C,$ and D are the coordinates of the four border recognition points for video line e . Total ventricular volume can be obtained by applying the equation:

$$V = \sum_{n=1}^{N-1} \Delta V_n \quad (\text{Eq 2})$$

in which N is the number of horizontal video lines traversing the video image.

The left panel in Figure 7 shows a computer-generated three-dimensional surface display of the volume function $dV(e,t)$ derived from Equation 1. The length (cm) axis represents the distance from the base or the top part of the ventricle to the apex or the bottom tip of the ventricle. The time (sec) axis represents elapsed time for successive beats. The iso-volume contour lines inscribed on this surface represent increments of 0.2 ml. The panel on the right is a contour map with twice the number of contour lines each having one-half the contour increment of those inscribed on the surface on the left panel, but which are viewed from directly above. This combination of formats is used so that exact coordinate values of features of interest on the surface can be determined from the contour map.

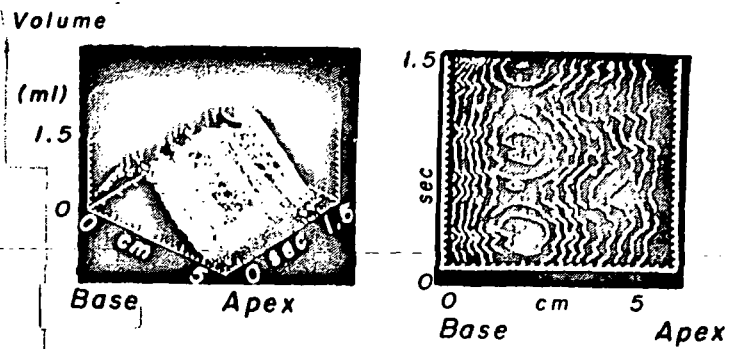


Figure 7. Computer-generated display of changes in regional volume of left ventricle of dog with time. Data were obtained from biplane roentgenographs recorded on videotape during injection of 8 ml of roentgenographic contrast medium into the left ventricle of an intact anesthetized dog. The surface represents 20,000 videometric data measurements (10 bits each) collected over a period of 1.5 seconds. Left: oscilloscopic display of volume of 0.5 mm-thick elliptical cross-sections of the left ventricle plotted against position of the sections from base to apex (in centimeters) and against time in seconds. Isovolume lines represent increments of 0.2 ml. Right: contour plot of distribution of volume in the left ventricle of a dog calculated from the surface on the left. Contour lines delineate volume increments of 0.1 ml.

A function considered to be of extreme importance in diagnosis of cardiac disease is the tension within the wall of the heart as a function of time and as a function of the coordinates on the surface of the heart chamber. In general, this function has been calculated from thin-wall equations which require that there be no radial stress in the wall of the chamber. This assumption will be used here since the purpose of this paper is to illustrate the data acquisition and display technique and not the physiology of heart contraction. An experiment was performed whereby the left ventricle of a canine heart was completely isolated by surgical means and suspended within the transirradiated space of the biplane videometry system. The coronary circulation of the heart was perfused with blood which did not contain radiopaque contrast media and, therefore, the heart wall was not x-ray opaque. However, the experiment was contrived so as to

have blood containing contrast media pumped through the left atrial and ventricular chambers rendering them radiopaque. The resulting orthogonal silhouettes are shown in Figure 8 and include both the epicardium (the outer surface of the left ventricle) and the endocardium (the internal surface of the left ventricle). Digitization of the epicardial and endocardial borders in the manner previously described (the endocardial surface is outlined in Figure 8) allows the change in thickness of the myocardium (heart muscle) with respect to the cardiac cycle to be modeled.

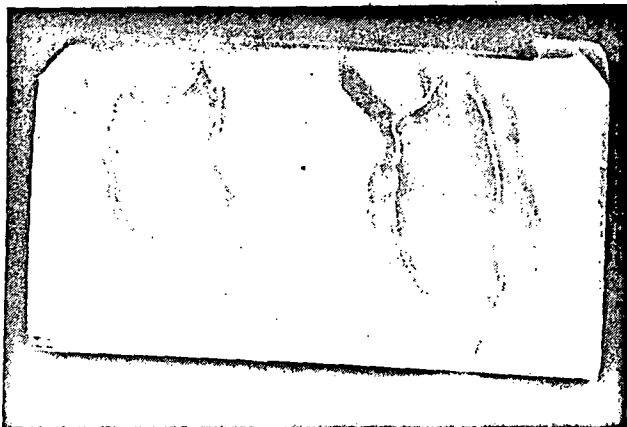


Figure 8. Photograph of a television monitor containing orthogonal biplane projections of an isolated left ventricle of a dog. Both epicardial and endocardial borders can be recognized by electronic contour system (the endocardial border recognition is shown) resulting in ability to measure thickness of wall for two orthogonal projections. The coronary circulation of this ventricle was perfused with nonopacified blood. However, the ventricle was pumping blood which contained radiopaque contrast media, thus the interior chamber of the ventricle is opaque while the wall is not.

Figure 9 illustrates a surface display of the tension calculated from the pressure within (measured through a catheter) and without (ambient) the isolated left ventricle and from the curvature of the ventricle as measured by the videometry system from the two orthogonal projections. The length axis of this figure is the distance from the base to the apex of the heart while the perimeter axis is the angular distance around the ventricle from an arbitrary starting point. Isotension lines depicting regional stress relationships and the distribution of tension over the wall are superimposed upon the surface.

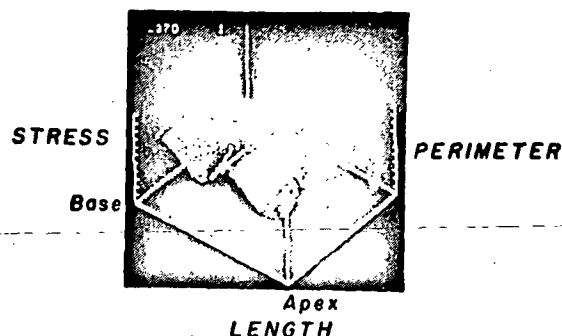


Figure 9. Computer-generated display of stress in the wall of the left ventricle calculated in the plane of the elliptical discs. Figure is in the format of Figure 7. Stress is illustrated as a function of length, the distance from the base to the apex of the heart, and of angle around the heart perimeter beginning at an arbitrary point on the surface. Isotension lines are superimposed upon the surface. The stress at each point in this figure was calculated from the thin-wall equations and is proportional to the internal pressure times the radius of curvature in the plane of the discs at the corresponding point on the surface of the ventricle.

Figure 10 illustrates a computer-generated stereo reconstruction of the structure of the endocardium in correct spatial relationship with the epicardium. Each surface was generated using the mathematical model described previously. The external surface or the epicardium is plotted at a low brightness level, thus making it appear transparent and allowing one to visualize the endocardium within the epicardium.

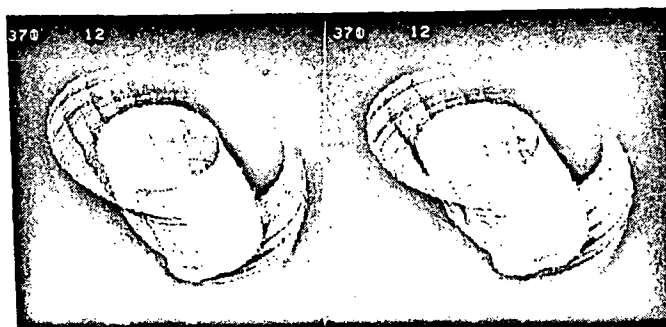


Figure 10. Computer-generated three-dimensional reconstruction of the surface of the endocardium and the epicardium as measured from the biplane images of a canine left ventricle. Data were obtained from biplane roentgenographic

analysis of an isolated left ventricular preparation. Both the endocardium and the epicardium were constructed using the mathematical model discussed in the text. The interior or endocardial surface is plotted with normal brightness range. The exterior or epicardial surface is plotted at a constant low brightness so as to appear translucent. This format provides detailed qualitative analysis of the thickness of the ventricular wall.

Figure 11 depicts a computer-generated three-dimensional reconstruction of a left ventricular surface inscribed with isotension contour lines. These contour lines have been inscribed around the surface of the epicardium in a 1:1 relationship such that the isotension line for any point represents the tension calculated for that point on the surface of the ventricle.

The entire biplane videoangiograph system and videotape recorder developed in the animal laboratory has been duplicated in the clinical catheterization laboratory. Various clinical procedures are being conducted with this system and the videotape recordings are hand carried to the video and computer-processing laboratory. To date several hundred patients have been analyzed using this system.

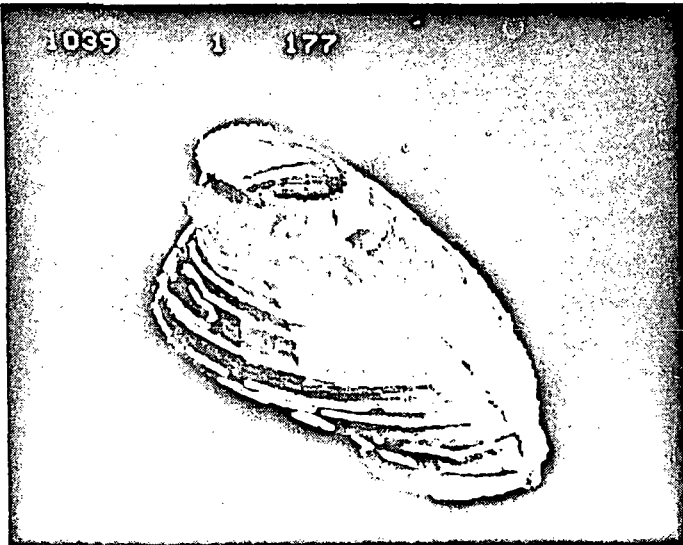


Figure 11. Computer-generated three-dimensional display of the epicardium of a left ventricle inscribed with mean isotension contours. Contours were calculated from thin-wall equations. This format allows detailed visual correlation of a quantitative function with the geometry of the structure of the left ventricle. Dynamic displays of these data can be accomplished with video disc recording/replay and allow

both temporal and spatial analysis of the function of the left ventricle.

An example of a computer-generated simulated three-dimensional display in stereo of the left ventricle of a human is illustrated in Figure 12.

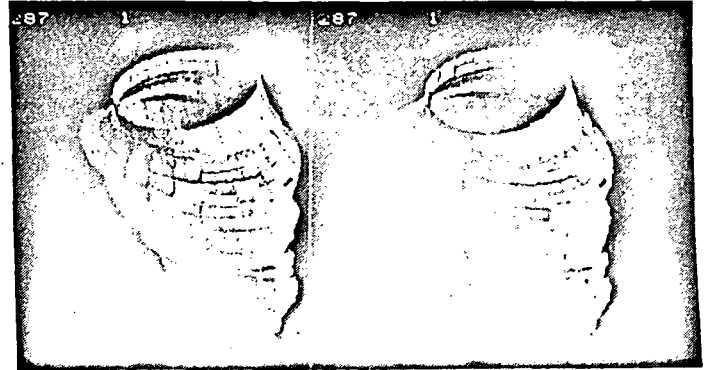


Figure 12. Computer-generated three-dimensional display of the left ventricle of a human patient. Data were obtained from a clinical laboratory biplane video roentgenography system and analyzed in the videometry-computer laboratory.

Much information can be obtained by studying the extent and velocity of contraction of regions of the ventricular wall. One might imagine that a portion of the muscle which has been deprived of blood circulation because of destruction of a coronary artery supplying that region may have difficulty contracting; in fact, it is known that these regions bulge outward due to high intraventricular pressure during a heart contraction. In order to facilitate a study of such phenomena, dynamic displays of both the geometry and of functional parameters of the left ventricle have been developed.

Dynamic displays of computer-generated simulated three-dimensional functions are produced by first plotting the display on a gray-level storage scope, the Princeton Electronic Products (PEP) 400 Video/Graphics Storage Terminal. This terminal stores distributions of charges on the face of a storage tube which can be nondestructively read with a video raster scan. The distribution of charges constituting the graphic image can be placed on the face of the storage tube by the computer in much the same way an optical image is formed on the phosphor of a conventional cathode-ray tube. A special purpose controller has been designed to interface the PEP terminal with the video and computer systems described in this paper. The controller processes all communication

between the operator, computer, and PEP unit to ensure operational fidelity, to provide on-line status checks, and to prevent tube damage. General purpose computer programs have been written to facilitate a wide range of applications for which the PEP can be used, including storage of computer-generated displays of bi-level or full gray-scale graphical images. Since this device converts computer-generated graphical displays into video format, these displays can be subsequently recorded on a video disc or on videotape. A sequence of such displays of, for instance, the structure of the left ventricle representing sequential points in time during the cardiac cycle, can be stored one-by-one on the video disc recorder for later play-back either in real-time slow-motion, reverse motion, or stop-action. The images replayed from the video disc can be recorded on videotape to provide more permanent, long-term storage. The movie-like dynamic display of such data can facilitate the evaluation of temporal and spatial details and relationships within the data structure.

Discussion

Computer-aided acquisition of biplane video roentgenographic data depicting the dynamic action of chambers of the heart results in the accumulation of a vast quantity of data. Since this system generates about 50,000 data points per second, one can appreciate the necessity for computer reduction, analysis, and comprehensive display of the data. The simulated reconstruction of the left ventricle provides subjective evaluation of data which is in a form readily identifiable with the real organ. Inscribed isolevel contours depicting the magnitude of any selected function on the surface of the structure provides quantitative data in accurate geometric relationship to the anatomy of the structure. The ability to rotate the display to any desired view can be used to enhance the study.

Simulated three-dimensional displays of surfaces representing multivalued functions may allow the pattern recognition ability of the investigator and/or automated methods to identify various functional diseases of the heart. For instance, a dynamic display of the stress over the surface of a ventricular chamber as a function of cardiac phase may isolate a point in the cycle at which stress attains an abnormal peak. At the present time, only a qualitative estimate of the magnitude of the peak can be obtained. How-

ever, a relatively accurate estimate of the position on the surface of the endocardium of that peak can be obtained.

Complete analysis of the distributions of intensity of the video pictures obtained from this orthogonal-biplane system should lead to an ability to determine more accurately the actual structure of the entire surface of the ventricle. This laboratory and others (Ref. 3,9) have recently derived methods for determining distributions of two-dimensional intensities from their orthogonal one-dimensional projections. This will allow the determination of the actual outline of each cross-section of the heart traversed by the video lines. This will increase the accuracy of not only volume measurements but also the stress calculations since radius of curvature will then be more accurately known. Accurate measurements of the ventricular wall may result in the ability to determine not only the degree but the locality of the disease affecting the heart under study.

We feel that data derived from the methods described will greatly enhance the accuracy of diagnosis of diseases of the heart and other organs; but procurement of such data necessitates the successful intimate interaction between x-ray photo-optical instruments, computer analysis techniques, and most importantly, the investigator. Although the cost of this developmental system in our laboratories is high, a duplicate system, including the contouring processor, the A/D conversion system, the analog multiplexer/modulator, and even a small computer for analysis would be only 20-30% of the cost of the original biplane roentgenograph system. In addition to analysis of heart function, this system can be used to calculate flows within and geometries of other organs, such as the kidneys, liver, spleen, individual arteries and veins, and lung.

Acknowledgment

The authors are indebted to Ms. Jean Frank and her coworkers for secretarial and graphic assistance, and to Mr. Don Hegland and Mr. Merrill Wondrow for assistance with the video equipment.

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III.

August 31, 1972

Department of Physiology
and Biophysics

Mr. Ray Sutton
Director of Programs
for University Affairs
National Aeronautics and
Space Administration
Ames Research Center
Moffett Field, California 94035

Dear Mr. Sutton:

Subject: Work statement for the sixth year (November 1, 1972-October 31, 1973)
of research grant NGR 24-003-001, "Studies of the effect of gravitational
and inertial forces on cardiovascular and respiratory dynamics"

The work planned for the sixth year of the investigative program supported
by this grant will be in close accord with the projection contained in the
original grant request and the last work statement submitted September 30, 1971.

Introduction

Cardiac function and the functional reserve of the heart are determined
primarily by the functional status of the myocardium, and particularly of its
contractile elements, the cardiac muscle cells. Up to the present, no reliable
practically applicable method has been developed for determining the cardiac
reserve (i.e., the functional status of the myocardium of intact animals or
man).

The end product manifestations of the function of the myocardial contractile
elements (i.e., blood flows and central circulatory pressures) can be measured
with relative ease. However, due to the tremendous capability of the cardiac
muscle cell to adjust its mechanical work output in response to passive changes
in its resting length or changes in its neuronal drive or chemical-humoral
environment, it is well known that measurements of cardiac output and pressures
do not provide a sensitive index of the actual functional status of the
myocardium.

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The primary function of cardiac muscle cells is to generate the cyclic changes in length and tension in the myocardium required to generate the intrachamber pressures necessary to propel the requisite volumes of blood through its chambers. Basically, therefore, direct studies of the functional status of the myocardium in the intact circulation system require development of methods capable of measuring the length and tension of the myocardial walls and their rates of change over as complete an anatomical extent of the cardiac chambers as possible and the full instant-to-instant temporal extents of individual cardiac cycles.

Since the cardiac chambers are irregularly shaped and exhibit regional differences in wall thickness, measurements of the pressures within and the volume of, for example, the left ventricle, which can be made with reasonable accuracy with currently available techniques, are not, unfortunately, a direct function of the length and tension in the walls of this chamber. Reasonably accurate approximations of the length and tension in these walls entails, as a minimum requirement, accurate knowledge of the shape and size of the chamber in three-dimensional space and, if possible, the thickness of these walls over their full anatomical extent.

Furthermore, to be of value in studies of the functional status of the myocardium, relatively large numbers of determinations (approximately 60/second) of the shape and size of the cardiac chamber should be made throughout individual cardiac cycles so that dynamic changes in absolute values and rates of change of length and tension in all regions of interest in the myocardium can be studied.

Due in large part to the extremely large volumes of data and calculations required for reasonably accurate estimates of the instant-to-instant change in dimensions and three-dimensional shape of the left ventricle throughout individual cardiac cycles, no practically applicable methods for obtaining these data are as yet available.

Current electronic data processing and computing techniques are capable of handling these volumes of data and computations in practically short periods of time. Current developments in television techniques are capable of high fidelity transformation and recording of roentgenographic image information into electromagnetic analogs in real time. Development of the requisite special purpose hardware and computer software techniques currently underway will make this electronic image information readily amenable to processing and comprehensible display to the investigator in practically short periods of time by use of very high speed and high volume data processing, computing, and display techniques.

Development of computer-based biplane roentgen videodensitometry and videometry in the physiology and biophysics laboratories of the Mayo Foundation has been carried out with these considerations in mind. The ultimate objectives are to develop practically applicable methods for more detailed studies of the dynamic geometry of the left ventricle in the intact

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circulation than has been possible heretofore, and to apply these methods to physiologic studies in the animal laboratory and to clinical investigative diagnostic studies in the patient cardiac laboratories at Saint Mary's Hospital in Rochester, Minnesota and ultimately to large primates during space flight.

This system, by an automated technique, divides the ventricular chamber into multiple successive cross-sections about 0.7 mm-thick covering its entire length and measures the orthogonal diameters of each of these 50-200 cross-sections sixty times each second. This requires a data accumulation rate of about 60,000 samples per second.

Clearly, collection of the volumes of data of this magnitude, which are required to obtain reasonably accurate information concerning dynamic changes in shape and dimensions of the ventricle, is not feasible on a routine basis by manual techniques.

Furthermore, transformation of these data to instant-to-instant determinations of shape, dimensions, position, and volume of the ventricle requires a similarly large number of arithmetic calculations. In addition, to attain real value for meaningful studies of cardiac contractility, this instant-to-instant anatomic information must be accurately synchronized with simultaneous measurements of intraventricular pressure so that calculations of the changes in the tension-length relationships of the myocardial wall generated by its contractile elements during successive instants in the cardiac cycle can be made.

These practically insurmountable requirements for rates and volumes of data collection by even semiautomated manual techniques, the extremely large number of arithmetic calculations required to transform these data to shape, dimension, position, and volume values, plus the requirement for accurate synchronization with one or more time varying simultaneous parameters, such as pressures, flows, and electrical events, and the added very large volume of calculations required to derive tension-length relationships and their rates of change covering the full anatomical and temporal extents of the ventricle and individual cardiac cycles, plus the problem of displaying in readily comprehensible forms the resulting multi-parameter data which varies in time over a three-dimensional anatomical structure has prevented the use, except to very limited degrees, of the full power of angiographic techniques for studies of cardiac contractility in intact animals or man.

The biplane roentgen videometry and videodensitometry CDC 3500 computer and display system has been developed to make this possible. Although the system is operational at its present stage of development, it is still undergoing important developmental alterations. These alterations will greatly increase its reliability, sensitivity, and methods of

Mr. Ray Sutton

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collecting information. Also, further development of computational algorithms and associated computer programs for calculations of shape, length, and tension changes, and particularly extension of operator-interactive variable time-base multidimensional stereoscopic display techniques for rapid generation of comprehensible displays of the very large volumes of data obtained by the system are highly desirable to facilitate their analysis and understanding.

The most important of the improvements in hardware for collection of the original 60-per-second biplane videoangiographic images of circulatory structures should be completed before embarking on intensive time-consuming and expensive studies of the systems capabilities and applications of these capabilities to physiologic studies.

The progress which has been made in these developments up to the present has demonstrated the practicality of application of these techniques both in the animal laboratory and in the human cardiac catheterization laboratory for diagnostic studies in patients with various types of cardiac disease.

Just as in the prior biomedical instrumentation and measurement techniques which were developed in these laboratories, such as: strain-gauge manometry, absolute reading ear and cuvette oximetry, densitometric continuous recording of circulatory dilution curves, the circulatory indicator (indocyanine green), and computer-based patient monitoring techniques, roentgen video techniques are being developed to fill investigative and practical diagnostic biomedical needs. These prior developments fulfilled the needs for which they were conceived, and just as important, have led to numerous investigative and diagnostic developments which were not foreseen until the results obtained by these new tools provided an expanded understanding of the investigative or diagnostic problems under study.

Similarly, we believe that development of a practical method for studies of the dynamic geometry of the left ventricle will fulfill, at least in part, the need for a better means of determining the functional reserve of the left ventricular myocardium during various types of circulatory stress including space flight as well as exercise in health and disease. Furthermore, this new tool will lead to a multitude of applications for study of cardiovascular physiology and cardiology, some of which can be foreseen at this time, but most of which very probably will not become evident until the experience gained and the information obtained by this new tool provide the background for further advances in this field.

The outline of the proposed work plan for this project submitted September 30, 1971 follows, along with an indication of the progress made on each section of this plan during the last year.

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Proposed Work Plan Research Grant NCR-24-003-001I. Critically important alterations in video image transducer hardware

A. Line-by-line logarithmic amplification.

Status*: completed.

B. Improved alternate biplane pulsing and blanking system.

Status: pulsing assembly - completed.

Scheduled completion date of blanking assembly: September 15, 1972.

C. Improved video cameras.

Status: completed to current stage of the art in fabrication of light sensing video camera targets (see attached manuscript by Ritman et al.).II. Developments in computational algorithms and associated computer software and display techniques plus tests of their reliability which are highly desirable to complete prior to large scale application of the system to physiological studies.

A. The problem of measuring the dimensions and shape of solid objects from orthogonal silhouettes.

1. Use of simultaneous biplane videodensitometry for reconstruction of the true shape of three-dimensional objects; e.g., the left ventricle.

Status: completed for orthogonal density profiles currently being extended to use of Fourier transforms and 3 to 180 multiple profiles in 0 to 180 degree range of views.

2. Real-time analog-to-digital conversion of biplane roentgen video images.

Status: scheduled completion date: January 1, 1973.

3. High-speed communications interface for real-time input of digitized roentgen video images into the laboratory's CDC 3500 computer.

Status: scheduled completion date: January 1, 1973.

4. Enhancement and reconstruction of digitized video images using special filtering, transformation, and subtraction techniques.

Status: in process.

5. Digital arithmetic hardware for large array processing; e.g., digitized video images.

Status: scheduled completion date January 1, 1973.

* Status of project as of September 1, 1972.

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6. Development of operator-interactive computer-generated multi-dimensional static and variable time-base display techniques.

Status: In process (see attached manuscript by Greenleaf et al.)

7. Tests of the reliability of the biplane roentgen videodensitometric system for measurement and display of the shape, dimension, position, and volume of solid objects, particularly the left ventricle.

Status: in process.

III. Applications of the orthogonal roentgen videodensitometry-computer system to studies of cardiovascular physiology.

- A. Studies with the completely isolated working left ventricle during controlled heart rates and different inotropic interventions to verify and develop techniques for measurement, display, and study of changes in shape, volume, segmental lengths, and wall thickness of a working heart under ideal multiple view conditions simultaneously with intraventricular pressures and flows, plus the multiple parameters relating to cardiac contractility which can be computed therefrom.

Status: Development of surgical and recording techniques completed. Four successful preparations have been studied.

- B. Extend these studies to anesthetized immobilized dogs during:

1. Different inotropic interventions (intra-aortic acetylcholine, angiotensin, plus sympathomimetic and autonomic blocking agents) over a wide range of heart rates.

Status: in process.

2. Selective stimulation and surgical denervation of cardiac sympathetic and parasympathetic nerves.

Status: in process.

3. Selective coronary occlusions.

Status: proposed.

4. Compare the changes in shape, position, and dimensions of the left ventricle obtained from biplane videoangiograms with simultaneous determinations by sonar echocardiography.

Status: in process.

5. Study of the effects of intraventricular injections of roentgen contrast medium on left ventricular dynamics.

Status: in process.

- C. Applications of orthogonal roentgen videodensitometric techniques for diagnostic studies in cardiac patients.

Status: in process.

- D. Extend these studies to unanesthetized free-ranging dogs and chimpanzees.

Status: proposed.

- E. Other circulatory problems requiring the use of orthogonal roentgen videodensitometry.

1. Function of the pericardium.

Status: in process.

2. Studies by orthogonal roentgen videodensitometry of blood flow in nearly every vessel in the systemic, pulmonary, or coronary circulations with internal diameters of greater than 1-2 mm, using:

- a. Differences in mean transit time, cross-sectional area method.
b. The Stewart-Hamilton indicator-dilution principle.

Status: in process.

3. Studies of end-diastolic, end-systolic, and stroke volumes of the ventricles by the indirect Holt indicator washout method using dilution curves of a roentgen contrast medium recorded simultaneously from contoured videodensitometer sampling windows tailored to fit the whole ventricle, ascending aorta, or any portions thereof.

Status: in process.

4. Studies of mixing characteristics of contrast media in the cardiac chambers using regional intracardiac dilution curves obtained by simultaneous orthogonal roentgen videodensitometry and recorded simultaneously from multiple sites covering all regions of interest over the chamber under study.

Status: in process.

5. Studies of valvular regurgitation by the upstream sampling technique using dilution curves of a roentgen contrast medium recorded simultaneously from monoplane or orthogonal videodensitometer sampling windows tailored to cover the entire up- and downstream cardiac chambers or any portions thereof.

Status: in process.

6. Study of the effect of ventricular assist devices on the dynamic geometry of the left ventricle.

Status: completed.

- IV. Applications of the orthogonal roentgen videodensitometry-computer system to study the effects of the gravitational-inertial environment on the cardiorespiratory system.

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- A. Spatial distribution of pulmonary blood flow.
Status: in process.
- B. Regional movements and volumes of lung parenchyma.
Status: in process.
- C. Use of orthogonal video roentgenography for studies of regional lung dynamics.
Status: in process.
- D. Use of lung parenchymal markers in studies of regional pulmonary blood flow.
Status: in process.
- E. Use of a water-immersion respirator for control of respiratory rates and volumes during studies of regional pulmonary dynamics.
Status: in process.
- V. Modification of the pulmonary effects of gravitational-inertial forces by liquid breathing.
 - A. Regional parenchymal movements and volumes.
Status: in process.
 - B. Spatial distribution of pulmonary blood flow.
Status: in process.
 - C. Use of lung parenchymal markers for study of regional pulmonary blood flow by the microsphere embolization techniques.
Status: in process.
 - D. Cardiovascular effects of liquid breathing.
Status: in process.
- VI. Application of the orthogonal roentgen videodensitometry system to densitometric studies of the vertebrae.
Status: proposed.

It is believed that the results of the investigations outlined herein, and future investigations made possible by these techniques will provide a better understanding of the physical and physiologic effects of various types of circulatory stress including the changes in the magnitude and direction of the gravitational-inertial force environment on the heart and lungs of intact healthy men and the associated regional variations in pulmonary perfusion and ventilation than has been possible heretofore. It is hoped that ultimately these techniques may be applicable for sophisticated studies of the alterations in circulatory and respiratory function during space flight in large primates or man.

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The proposed budget for the 1972-1973 grant period is enclosed. If further information would be helpful to you in regard to this proposed work program and budget for the upcoming year of this research grant, I would be pleased to attempt to supply the additional information at your request.

Sincerely,

Earl H. Wood, M.D., Ph.D.

BHW:JF

Enclosures: 2

(Manuscript by Ritman et al.
Manuscript by Greenleaf et al.)

IV. List of Publications During the Period October 1, 1971 to October 1, 1972.

1. Smith, H. C., R. L. Frye, D. E. Donald, G. D. Davis, J. R. Pluth, R. E. Sturm, and E. H. Wood:
Roentgen videodensitometric measure of coronary flow. Determination from simultaneous indicator-dilution curves at selected sites in the coronary circulation and in coronary artery-saphenous vein grafts.
Mayo Clinic Proceedings 46:800-806 (December) 1971.
2. Sass, D. J., E. L. Ritman, P. E. Caskey, N. Banchemo, and E. H. Wood:
Liquid breathing: Prevention of pulmonary arterial-venous shunting during acceleration.
Journal of Applied Physiology 32:451-455 (April) 1972.
3. Coulam, C. M., J. F. Greenleaf, A. G. Tsakiris, and E. H. Wood:
Three-dimensional computerized display of physiologic models and data.
Computers and Biomedical Research 5:166-179, 1972.
4. Greenleaf, J. F., E. L. Ritman, C. M. Coulam, R. E. Sturm, and E. H. Wood:
Computerized measurement and display of dynamic changes in shape and volume of solid objects derived from biplane roentgen videograms with particular reference to cardioangiography.
Computers and Biomedical Research (in press, August 1972).
5. Wood, E. H.:
Some effects of changes in the gravitational-inertial force environment on the heart and lungs.
Proceedings Fourth International Man-in-Space, Yerevan, U.S.S.R. October 1-5, 1971 (in press).
6. Wood, E. H., E. L. Ritman, R. E. Sturm, S. Johnson, P. Spivak, B. K. Gilbert, and H. C. Smith:
The problem of determination of the roentgen density, dimensions and shape of the homogeneous objects from biplane roentgenographic data with particular reference to angiocardiology.
Proceedings of San Diego Biomedical Symposium, February 2-4, 1972, pp 1-43.
7. Miyazawa, K., H. C. Smith, E. H. Wood, and A. A. Bove:
Roentgen videodensitometric determination of left-to-right shunts in experimental ventricular septal defect.
American Journal of Cardiology (in press).
8. Smith, H. C., R. E. Sturm, and E. H. Wood:
A videodensitometric system for measurement of vessel blood flow, particularly the coronary arteries, in man.
American Journal of Cardiology (in press).
9. Smith, H. C., J. F. Greenleaf, E. H. Wood, D. J. Sass, A. A. Bove:
Measurement of regional pulmonary parenchymal movement in dogs.
Journal of Applied Physiology (in press).

10. Bursch, J. H., E. L. Ritman, E. H. Wood, and R. E. Sturm:
Roentgen videodensitometry.
Chapter in History of Indicator Dilution (Dr. D. A. Bloomfield,
editor) (in press).

11. Yipintsoi, T. and E. H. Wood:
The history of circulatory indicator dilution.
Ibid.
12. Ritman, E. L., R. E. Sturm, and E. H. Wood:
A biplane roentgen videometry system for dynamic (60/second)
studies of the shape and size of circulatory structures, particularly
the left ventricle.
Symposium on the Use of Video Technology in Cardiovascular Research,
American Journal of Cardiology (Dr. M. L. Marcus, editor) (in press).
13. Smith, H. C., R. E. Sturm, and E. H. Wood:
A videodensitometric system for measurement of vessel blood flow,
particularly the coronary arteries in man.
Ibid.
14. Tsakiris, A. G., R. E. Sturm, and E. H. Wood:
Experimental studies of the mechanisms of closure of cardiac valves
using roentgen-videodensitometry.
Ibid.
15. Ritman, E. L., S. A. Johnson, R. E. Sturm, and E. H. Wood:
The television camera in dynamic video angiography.
Radiology (in press).
16. Greenleaf, J. F., E. L. Ritman, E. H. Wood, R. L. Frye, R. A. Robb, and
S. A. Johnson:
Dynamic computer generated displays for study of the human left ventricle.
Proceedings Symposium "Developments in Electronic Imaging Techniques",
Society of Photo-optical Instrumentation Engineers, October 16-19, 1972,
San Francisco (in press).
17. Smith, H. C., R. L. Frye, G. D. Davis, G. K. Danielson, J. R. Pluth,
R. B. Wallace, R. E. Sturm, and E. H. Wood:
Measurement of flow in saphenous vein-coronary artery grafts by
roentgen videodensitometry.
Circulation 44:Supplement II-107, 389 (October) 1971. Abstract
18. Gilbert, B. K., M. Bourgeois, and E. H. Wood:
Relationship between atrial-ventricular stimulus interval and
cardiac performance in dogs with chronic A-V block.
Federation Proceedings 31:348 (March-April) 1972. Abstract
19. Sass, D. J., J. F. Greenleaf, P. E. Caskey, E. L. Ritman, S. A. Johnson,
H. F. Helmholtz, Jr. (and E. H. Wood):
Blood pH in dogs breathing oxygenated FC 80 fluorocarbon.
Federation Proceedings 31:348 (March-April) 1972. Abstract

20. Sass, D. J., W. Van Norman, S. Zahn, and E. H. Wood:
Digital computer analysis of circulatory and respiratory pressures in water-immersed dogs breathing liquid in force environments of 1 and 7Gy.
~~Aerospace Medical Association preprint, 1972-Annual Scientific Meeting~~
May 8-11, 1972 pp 242-243. Abstract

21. Ritman, E. L., S. A. Johnson, R. E. Sturm, and E. H. Wood:
Distortion of dynamic roentgen angiographic images by the video camera..
Proceedings 3rd Annual Meeting Biomedical Engineering Society,
April 7-8, 1972, Johns Hopkins University, Baltimore, Maryland,
p 68. Abstract

22. Bourgeois, M. J., B. K. Gilbert and E. H. Wood:
Relation of aortic diastolic pressure decay and peripheral vascular resistance.
The Physiologist 15:91 (August) 1972. Abstract

23. Bursch, J. H., P. H. Heintzen, and R. Simon (introduced by E. H. Wood):
Roentgen videodensitometric determination of the residual fraction of the normal left ventricle and regurgitant fraction in experimental aortic regurgitation.
The Physiologist 15:96 (August) 1972. Abstract

24. Greenleaf, J. F., H. C. Smith, D. J. Sass, E. L. Ritman, and E. H. Wood:
Regional distribution of blood flow in the lungs of dogs in left decubitus position.
The Physiologist 15:53 (August) 1972. Abstract

25. Ritman, E. L., R. E. Sturm, and E. H. Wood:
Left atrial contribution to left ventricular end-diastolic and ejection volumes.
The Physiologist 15:250 (August) 1972. Abstract

26. Ritman, E. L., R. L. Frye, G. D. Davis, B. D. Rutherford, G. T. Gau, R. E. Sturm, and E. H. Wood:
Total and regional left ventricular performance by operator-interactive computer-based analysis of videoangiograms.
Circulation (supplement) (in press, October 1972). Abstract

27. Smith, H. C., R. L. Frye, E. H. Wood, G. D. Davis, G. K. Danielson, J. R. Pluth, and R. B. Wallace:
Sequential measurement of saphenous veingraft flows and dimensions.
Circulation (supplement) (in press, October 1972). Abstract